

Microalgae Production from Power Plant Flue Gas: Environmental Implications on a Life Cycle Basis

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National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

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Prepared under Task No. DO11.4010



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EXECUTIVE SUMMARY

Background

Electrical power plants are responsible for over one-third of the U.S. emissions or about 2.2×10^9 t carbon dioxide (CO₂) per year. Power-plant flue gas can serve as a source of CO₂ for microalgae cultivation, and the algae can be cofired with coal. The study objective was to conduct a life cycle assessment (LCA) to quantify the environmental benefits of recycling CO₂ from power plants for microalgae production. Specifically, electricity production via coal firing versus coal/algae cofiring was compared.

Key LCA Results

The LCA, which accounts for all the inputs and outputs to a given process option, demonstrates that there are potentially significant benefits to recycling CO₂ toward microalgae production. Based on the LCA results, lower net values for the algae cofiring scenario were observed for the following using the direct injection process (in which the flue gas is directly transported to the algae ponds):

- SO_x and NO_x
- Particulates
- CO₂ and methane
- Fossil energy consumption

Carbon monoxide and hydrocarbons (except methane) emissions were statistically similar. However, the algae cofiring scenario exhibited higher water-borne emissions as indicated by the chemical oxygen demand (COD) values.

Four impact assessment categories were also evaluated to further illuminate the differences between the two scenarios: greenhouse potential, depletion of natural resources, air acidification potential, and eutrophication potential. The lower emissions of greenhouse gases (GHGs) such as carbon dioxide and methane emissions—although not regulated or mandated by state or national laws—are also desirable attributes as they lead to lower greenhouse potential for the coal/algae cofiring scenario. Lower values for the algae cofiring scenario, when compared to the coal-firing scenario, were also observed for the impact assessment category of air acidification potential. However, impact assessment for depletion of natural resources and eutrophication potential showed much higher values. For Scenario 2, the higher depletion of natural resources results from higher consumption of natural gas and oil, which have lower reserves than coal. When coal is displaced by algae, its positive impact is smaller due to larger coal reserves. In other words, if a natural gas fired plant were considered, depletion of natural resources would not be as high for Scenario 2. The eutrophication potential values are higher because of fertilizer consumption during algae production. Fertilizer production results in relatively high COD values and phosphate emissions, and only the algae cofiring scenario has this particular burden.

Conclusion

The algae cofiring scenario distinguishes itself by demonstrating lower GHG (a global unregulated environmental criterion) and air pollutant burdens (local regulated environmental criteria). However, these benefits have to be balanced with higher natural gas and oil consumption and higher eutrophication potential. This LCA gives us an overall picture of impacts across different environmental boundaries. Hence, it can help the decision-making process at companies like Rio Tinto Energy Group (a mining/energy company in Australia) and Arizona Public Service that are considering microalgae production as an avenue for GHG mitigation.

1 INTRODUCTION

The United States generates about 5.7 Gt ($G \equiv 10^9$) of carbon dioxide (CO_2) per year amounting to about 22% of the worldwide anthropogenic emissions. U.S. anthropogenic CO_2 emissions for 2000 are listed by sector in Table 1 (EIA 2000). Electrical power plants are responsible for 38% the U.S. emissions and 7% of the world's CO_2 emissions from energy use (USDOE 2000).

CO_2 is a major greenhouse gas (GHG), and its physical capture from fossil-fuel power-plants has been considered as a potential remediation option since Marchetti (1977) first proposed the disposal of the captured CO_2 in the deep ocean. Several investigators have since studied a plethora of options for CO_2 capture from power plants—which are stationary, concentrated sources of the gas—and its subsequent disposal or use. Thus, CO_2 capture is a common step for most of the remediation options.

Table 1. U.S. anthropogenic CO_2 emissions for 2000

Sector	Gt of carbon/year	Gt of CO_2 /year	% of Total
Transportation	517	1896	33.3
Industrial	470	1723	30.3
Commercial	259	950	16.7
Residential	306	1122	19.7
Total	1552	5691	100.0

In a general assessment of alternative processes for capturing CO_2 from existing coal-fired power plants, Herzog et al. (1991) concluded that capture is currently technically feasible, but that the most efficient available technology will reduce energy efficiency of utility steam plants by about 30% and will increase the price of electricity by 80%, even before disposal costs are added. These results are consistent with a study by the Electric Power Research Institute (EPRI) on CO_2 capture and disposal (Booras and Smelser 1991). Emerging and future electricity generation technologies have the potential to significantly reduce these costs.

Besides disposal, another potential sequestration option is to find recycle opportunities for power plant CO_2 as a feedstock for industrial products or processes or as a component of alternative fuels. For CO_2 recovery, the monoethanolamine (MEA) absorption process is commonly employed and is the heart of the steam host requirement. The two commercial U.S. CO_2 recovery facilities use MEA absorption technologies and produce a food- and beverage-grade product. The total industrial utilization of CO_2 today in the U.S. is about 2% of the CO_2 generated from power plants. However, in about 80% of the applications, as in enhanced oil recovery (EOR) and the food industry, CO_2 used is rapidly returned to the atmosphere. While niches may be found for some utilization, it is unlikely that industrial use can sequester more than a minor fraction of the emitted CO_2 from power plants. Use in fuels is feasible, but external energy inputs required to synthesize the fuels can be much more efficiently used to serve energy markets directly. Conversion of CO_2 to microalgae is also a sequestration option; however, as in any other option, efficient recovery and delivery of the CO_2 are critical.

This study discusses the environmental implications of using power-plant flue gas as a source of CO₂ for microalgae cultivation and cofiring the algae with coal for electricity production.

2 MICROALGAE PRODUCTION

Microalgae are unique photosynthetic organisms given that they accumulate storage lipids in substantial quantities and thrive in high salinity water. In the United States, microalgae pond-systems are envisioned to be located in the desert Southwest because this area offers flat land, high incident solar radiation, few competing land uses, and large reservoirs of saline water. This minimizes land costs, while the use of saline water, not suitable for agricultural, domestic, or industrial purposes, minimizes competition with other uses for the limited supplies of fresh water in the Southwest. The algal mass produced from power plant CO₂ is a useful product with application in food, fuels, etc. The production of lipids from microalgae is a possibility because plant storage lipids could be among the best biomass feedstocks for producing renewable, high-energy liquid fuels such as diesel fuel. Alternatively, cofiring the algae with coal for electricity production is the option considered in this study, as this is a simpler approach not requiring extensive post-cultivation processing. Furthermore, unlike soybean-based biodiesel, the hexane emissions can be substantial for microalgae-based biodiesel (unpublished data).

2.1 CO₂ Recovery

Previous analysis has shown that CO₂ cost plays a central role in process economics, making the minimization of CO₂ cost a top priority (Kadam and Sheehan 1996). A rigorously derived CO₂ recovery-cost model is available in the context of microalgae cultivation using flue gas emitted by a typical 500 MW power plant located in the Southwestern United States (Kadam 1997). This model assumes a transportation distance of 100 km and night storage of CO₂ in the pipelines. The standard process includes MEA extraction, compression, dehydration, and transportation to the ponds, and produces a gas that is almost 100% CO₂. To evaluate if the flue gas could be directly utilized, an alternative case was devised that only includes compression, dehydration, and transportation to the ponds. This option delivers CO₂ to the ponds at a concentration of only 14%. Processing of flue-gas equivalent to a 50 MW capacity was also analyzed since it matches well with the CO₂ mitigation capacity of a 1000 ha pond system.

The comparison of processing options in the above study showed that the MEA extraction was less expensive than the direct pumping option as a penalty is levied on the latter in the form of compressing and transporting a seven-fold higher gas volume. However, as compression is costly and energy-intensive, the best strategy may be to eliminate it altogether. The direct pumping option should then be more economical. In the direct pumping scheme, night storage of CO₂ in the pipelines is not feasible and only a part of the emitted CO₂ can then be used for algae production. In this analysis this simpler and more economical approach of direct pumping was used.

Resource Assessment

Kadam and Brady (1996) conducted a geographical information system (GIS) based resource assessment study for algae production using CO₂ from the San Juan power plant (1800 MW) owned by Public Service of New Mexico (PNM). They concluded that a pond system capable of mitigating at least enough CO₂ from one 500 MW unit is feasible. However, a 50 MW capacity is assumed for this analysis, which corresponds to about a 1000 ha pond system and total CO₂ emissions of about 414,000 t/yr. It should, however, be noted that the size of the pond system does not affect the life cycle assessment (LCA) results which are normalized based on 1 MW of electricity produced.

3 PROJECT SCOPE

3.1 Study Objective

The study objective is to conduct an LCA to quantify the environmental implications of using power-plant flue gas as a source of CO₂ for microalgae cultivation and cofiring the algae with coal for electricity production. This approach is compared with the *status quo* of electricity production using coal alone. The LCA results would serve as a basis in the decision-making process for implementing the algae scenario.

3.2 Life Cycle Assessment Principles

LCA is a technique for assessing the environmental aspects and potential impacts associated with a product, by:

- Compiling an inventory of relevant inputs and outputs of a system (life cycle inventory [LCI])
- Evaluating the potential environmental impacts associated with those inputs and outputs
- Interpreting the results of the inventory and impacts in relation to the objectives of the study.

LCA studies the environmental aspects and potential impacts throughout a product's life (i.e., from cradle to grave) from raw material acquisition through production, use, and disposal. The general principle for extending the system boundaries, to include various processes involved in producing and using a product, is illustrated in Figure 1.

In the most straightforward and transparent approach to LCI interpretation, the inventory results may be used on an “as-is” basis to help identify and prioritize opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. A particular advantage of LCI applied in this way is its comprehensiveness. LCAs help detect the shifting of environmental burdens from one life cycle stage to another (e.g., lower energy consumption during use, achieved at the cost of much higher manufacturing energy consumption), or from one medium to another (e.g., lower air emissions at the cost of increased solid waste).

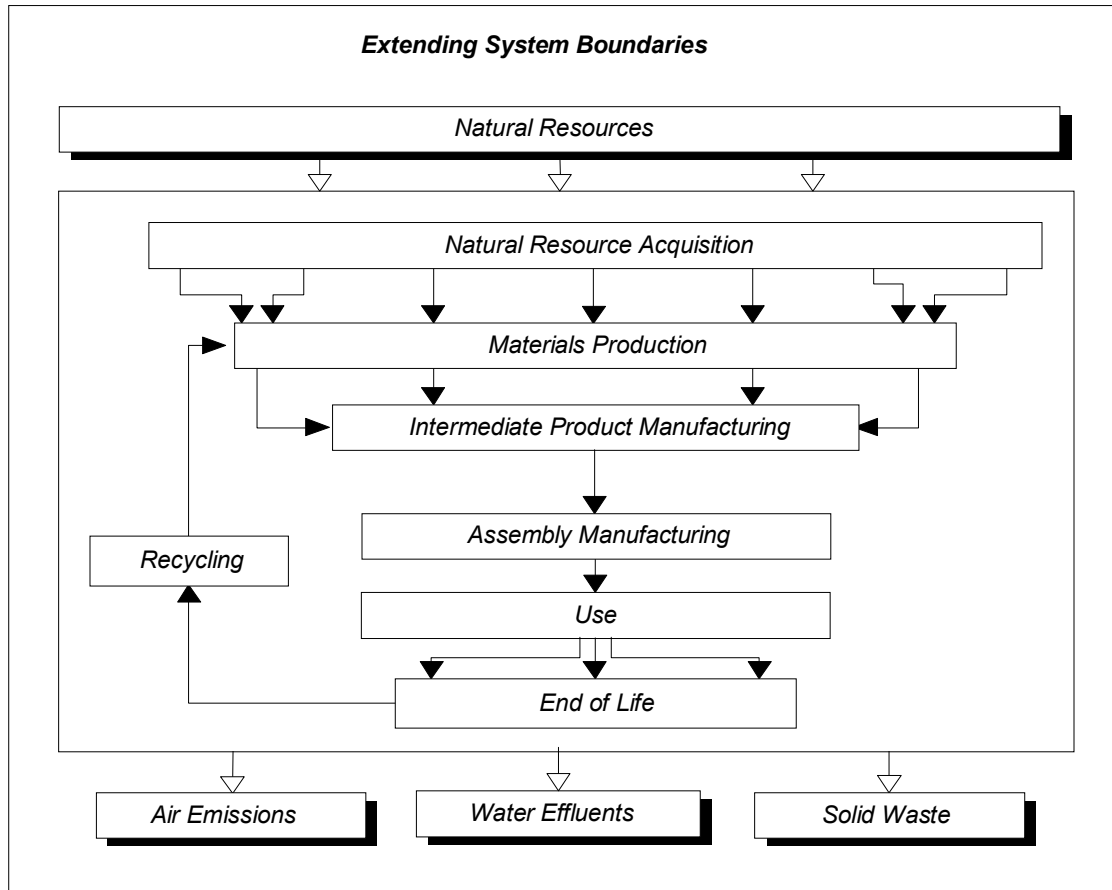


Figure 1. Schematic representation of extending system boundaries.

Because the number of flows calculated during an LCI analysis is often very large, subsets of the flows are sometimes consolidated or aggregated to facilitate interpretation, especially when two or more products or processes are being compared using LCA. This consolidation and aggregation of flows has been given the (perhaps misleading) name of life cycle impact assessment (LCIA). In fact, it is not the impacts of the environmental flows in the inventory that are estimated using LCIA. Instead, the inventory flows are consolidated and aggregated using information about their relative potential strength of influence on separate categories of potential environmental impacts, thereby generating indicators. The results within each LCIA impact category are useful for comparing one product or process with another, but have little meaning in an absolute sense (i.e., relative to estimating the actual environmental impacts of a product or process).

Because the results of an LCI and an LCIA are influenced by a significant number of assumptions and uncertainties, the interpretation phase usually includes some sensitivity analyses. This allows an assessment of the robustness of the baseline results, project assumptions, methodological choices, future scenarios, and uncertainties. In this study, data quality was assessed for its 1) precision, 2) completeness, 3) representativeness, 4) consistency, and 5) the origin of the data (measured, calculated, or estimated).

Principal aspects of LCI and LCIA are discussed briefly in the sections that follow. Further information about LCA methodology is provided in a number of publications from the Society of Environmental Toxicology and Chemistry (SETAC 1991; SETAC 1993a; SETAC 1993b; SETAC 1994), the U.S. Environmental Protection Agency (EPA) (EPA 1993a; EPA 1993b; EPA 1995a), the International Organization for Standardization (ISO 1996; ISO 1997), as well as other sources (Heijungs et al. 1992; SETAC–Europe 1992).

3.3 Methodology

3.3.1 Functional Unit

The comparison of different industrial systems can only be achieved if they perform the same function. Once this shared function is defined; a unit must be chosen in order to compare the systems on the same quantitative basis. All the energy and mass flows in the inventory are normalized to this functional unit. Examples of how this is done are presented below.

- The comparison of different indoor paints (solvent-borne, water-borne, etc.) could be made on the following basis:
 - * Function: covering a surface
 - * Functional unit: the quantity of paint required to cover 5 m² of wall (this function could be further refined to take into account secondary functions like opacity, washability, durability and lifetime, etc.)
- The comparison of different transportation fuels could be made on the following basis:
 - * Function: energy needed to travel 1 km
 - * Functional unit: the quantity of transportation fuel required to provide the necessary energy

3.3.2 Definition of System Boundaries

For each option being compared on a life-cycle basis, the corresponding systems are then determined (i.e., relevant processes to be included in the system are selected). The three main issues to address, for each of the systems, are discussed below.

- 1) Exhaustivity of the systems. The LCA theoretical principle implies that *each* material and constituent be studied and traced *back* to natural resources, and *forward* through final disposal. The strict application of this principle would lead to the study of almost every industrial process, because all industrial operations work within a complex network. In order to focus LCA projects on the main operations, quantitative rules are applied to exclude the constituents and ancillary materials whose impacts are estimated to be negligible compared to those of the overall studied system.
- 2) Identification of steps/operations that are different from one system to another. As the project focuses on a comparison, steps that are functionally equivalent for the compared products could be excluded from both systems. On the other hand, steps or operations that are not functionally equivalent for the compared products should be taken into account and included in the system boundaries.
- 3) Identification of coproducts and determination of the appropriate partitioning parameter. This facilitates proper allocation of a defined product's share of the total pollution, energy consumption, and material flows for which the process is responsible.

3.3.3 Interpretation: Life Cycle Impact Assessment

In this element of the LCA, after the inventory has been prepared, two further steps that need to be considered:

- 1) Whether and how to aggregate and/or consolidate the inventory data using information about each flow's relative potential strength of influence with respect to separate categories of potential environmental impact; and
- 2) Whether and how to aggregate the results of the step mentioned above, across the impact categories considered.

Note that the first of these two steps is pursued in addition to the LCIA, not as a replacement for it. Those attempting to develop a final “score” for comparing products or processes only use the second of these two aggregation steps. It was not used in this project because it requires value judgments (e.g., is water pollution more sinister than air pollution?), which are beyond the scope of this analysis.

4 SCOPING OPTIONS AND DECISIONS

This section presents the various parameters that should be considered in order to precisely define the scope of the project. These parameters can be addressed sequentially, as indicated in Figure 2. The process begins by first considering “project” level parameters that involve high-level choices that can have a profound impact on the general orientation and outcome of the project. These choices involve geographic, temporal, technical, and environmental aspects of the life cycle scenarios being studied. Next, we need to consider more specific product parameters, including the exact nature and form of the products studied and the type of application in which they are used. The third group of parameters involves the production processes used to make the product. The types of choices made for high-level project parameters influence both product- and process-related parameters. Finally, a group of parameters must be defined regarding the LCA methodology itself.

Subsequent sections address the separate scoping elements in turn, as follows:

Project Parameters	⇒	Section 4.1
Product Parameters	⇒	Section 4.2
Process Parameters	⇒	Section 4.3
LCA-Specific Parameters	⇒	Section 4.4

The key criteria that have been employed in selecting an option for each parameter are:

- Relevance to the project's goals
- Availability of data
- Time and cost constraints

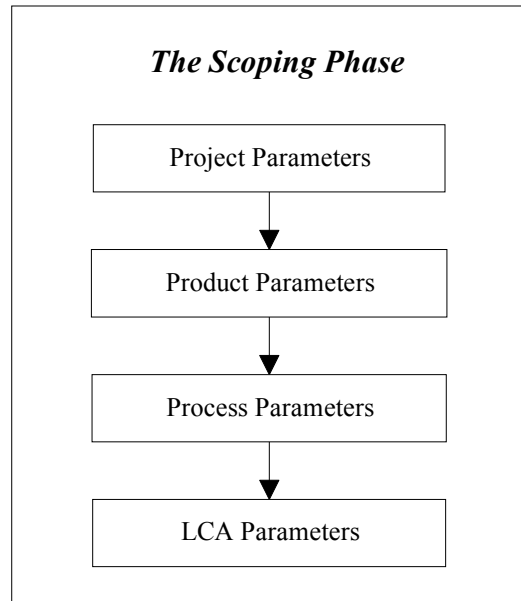


Figure 2. Elements of the scoping phase for life cycle analysis.

4.1 Project Parameters

4.1.1 General System Boundaries

Figure 3 shows the general system boundaries for the two scenarios considered in this study. In one scenario, electricity is produced using coal alone (Scenario 1). In the alternative scenario, power-plant flue gas is used as a source of CO₂ for microalgae cultivation and the algae is cofired with coal for electricity production (Scenario 2). Electricity production using coal represents the *status quo*; this LCA compares cofiring of microalgae, produced from flue-gas CO₂, with the *status quo*.

4.1.2 Environmental Issues Considered

The LCA methodology traditionally calls for complete mass and energy balances for each process, including energy consumption, raw material consumption, air emissions, water effluents, and solid waste. This comprehensive compilation exercise results in a quantification of all existing flows into the environment. However, this scheme has become increasingly questionable for the following reasons:

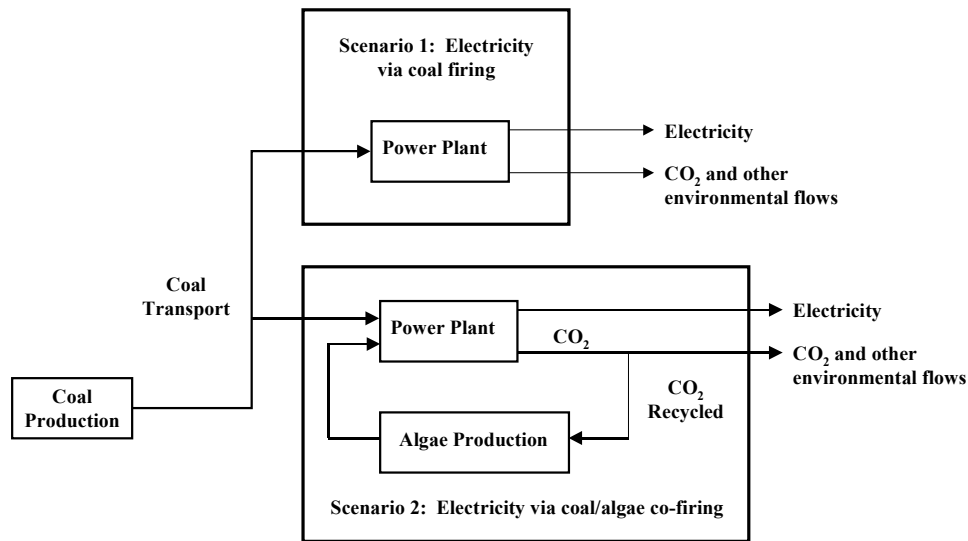


Figure 3. General system boundaries for the comparison of electricity production via coal firing versus coal/algae cofiring.

- **Practical Reasons:** An ever-expanding number of parameters can be tracked within an inventory, reflecting more comprehensive data measurements. For instance, including U.S. Toxic Release Inventory (TRI) data would result in a list of approximately 200 pollutants being released during gasoline production. Similarly, including radionuclide emissions from electricity production would result in tracking more than 150 specific flows. Therefore, managing such a large inventory list adds to the complexity of carrying out as well as interpreting the LCA because these additional flows should be collected for all sources within the system for the sake of consistency.
- **More Fundamental Reasons:** By restricting the inventory data collection to the information actually needed in a subsequent decision analysis, a more focused LCA can be carried out. This ensures that the issues at stake receive the highest priority and data quality. Some studies even restrict their data collection to pollutants contributing to a single effect, e.g., greenhouse gases.

Therefore, it is important to understand the issues or impacts that are of greatest concern to the users of the LCA (or decision-makers) and then tailor the data collection to meet their needs. It should be noted that an inventory number (e.g., quantity of lead) is only an indication of a potential impact. Additional data such as ambient concentration, pathways to human and ecological toxicity, and the existence of thresholds would be needed to assess the actual impact of this emission. These additional data are of the type required in risk assessment in which exposure data are collected for a few emissions at a single site. An actual LCA would need to gather these additional data for all inventory flows and for all sites included in the system boundaries (generally well over a hundred). Because the limitations of inventories are well known, this type of actual impact assessment is as difficult as it is impractical.

LCA should consequently be considered as providing an indication of potential environmental impact, complementary to actual impacts evaluated by other tools. The following steps were used to facilitate interpretation of the inventory results through impact assessment:

- **Classification:** The organization of inventory data into environmental impact and resource consumption categories, such as global warming potential, acidification potential, natural resource depletion, etc.
- **Characterization:** Weighted summing of inventory data within each environmental impact category, based upon each flow's relative strength of potential influence upon the identified environmental impact or effect.

The characterization step explicitly takes into account the latest scientific assessments of the uncertainty inherent in the equivalency factors, such as global warming potentials. In addition, the discussion accompanying the characterization results clearly states that the results of a characterization analysis serve strictly to normalize the multiple flows within the LCI with respect to a particular environmental issue in terms of their relative strength of potential contribution to that issue. Characterization is not in any way intended to estimate the actual impact of the emissions upon environmental issues.

Furthermore, some of the inventory flows themselves may be highly uncertain, with an estimable magnitude of uncertainty. This uncertainty is appropriately combined with the uncertainty inherent in the equivalency factors used in the characterization step. Table 2 indicates the environmental inventory flows and their corresponding impact assessment categories considered in this study.

Some of these environmental flows can potentially have impacts on the environment that go beyond the effects caused by the flow itself. For this study, the potential impacts of the life-cycle flows were assessed for the following impact assessment indicators: greenhouse effect potential, natural resource depletion, acidification potential, and eutrophication potential.

To calculate the impact indicators, each flow that is determined to be a contributor to one of these categories is weighted according to its impact in comparison to a set baseline. For example, the baseline is grams of CO₂ equivalent for the greenhouse effect potential indicator. The value for the flow is multiplied by this weighting factor to give an impact score for the particular flow. The impact scores for all contributing flows are then summed to give an overall impact score for the potential impact. The weighting of the environmental flows is based upon the best available scientific knowledge; however, the scores should be interpreted as potential impacts, not actual impacts. The exact methodology is discussed in more detail in Appendix B.

Table 2. Environmental inventory flows considered in the study

Environmental Flow	Associated Impact Category
<i>Natural Resources</i>	
Oil	Natural resources depletion ¹
Coal	Natural resources depletion
Natural Gas	Natural resources depletion
Other significant resources depending on decision rules	Natural resources depletion
<i>Water Effluents</i>	
Chemical oxygen demand (COD)	Eutrophication potential
Biological oxygen demand (BOD)	Eutrophication potential
Nitrates	Eutrophication potential
Phosphates	Eutrophication potential
Total suspended solids	Direct use ^a
Metals	Direct use
<i>Air Emissions</i>	
CO ₂	Greenhouse effect potential
CH ₄	Greenhouse effect potential
N ₂ O	Greenhouse effect potential
NO _x	Acidification potential
SO _x	Acidification potential
Particulate	Direct use
Hydrocarbons	Direct use
CO	Direct use
<i>Solid Waste</i>	
Nonhazardous	Direct use
Hazardous	Direct use
<i>Energy Use</i>	
Total primary energy	Direct use
Process energy	Direct use
Fossil fuel energy	Direct use

^aDirect use: Not used in any impact assessment category.

4.1.3 Geographical Scope

The focus of the project is the use of flue gas CO₂ for producing algae and its use in electricity production in Southwestern United States. However, the geographic scope of particular data items is dictated by actual plant locations, feedstock origins, sources of electricity, etc.

4.1.3.1 Algae Cofiring System

The CO₂ used for algae production originates in the Southwestern United States. The production of algae was assumed to occur in the vicinity of the power plant. However, for modeling purposes,

¹Inflows such as sand, limestone, etc. could be used in the natural resources depletion index although their impact is negligible because of their natural abundance.

U.S. average data are used. Data on ancillary materials needed for the conversion of CO₂ to algae are based on a U.S. average situation. The combustion of the coal/algae blend was assumed to follow individual combustion emissions profiles of coal and algae.

4.1.3.2 Electricity Production

Electricity production was based on Ecobalance Inc.'s (Bethesda, Maryland) data for the United States using coal. This database was considered to be applicable to electricity production in the Southwestern United States. However, U.S. Department of Energy's data for nation-wide average CO₂ emissions were used (USDOE 2000; Hong and Slatick 1994).

4.1.4 Temporal Scope

The issue here is whether to study a current situation, to model a future situation, or to model both current and future scenarios. Current and future scenarios could be quite different. For example, current scenarios would be limited to existing algae production technology. One reason for studying a mid- to long-term time frame, is that a widespread use of CO₂ derived algae in the near-term is not probable. However, the results of this study are data-driven, and the use of forecast or modeled (rather than current, empirically based) production, conversion, and end-use technology parameters would greatly increase the uncertainty in the final results.

For this study, the latter part of the current decade has been selected as the production period.

4.2 Product Parameters

4.2.1 Scenarios

Coal firing to produce electricity and CO₂ venting to the atmosphere is used as an existing scenario representing the *status quo*. Recycling CO₂ to algae production and cofiring the algae with coal to produce electricity represents the alternative scenario.

4.2.2 Functional Unit

The functional unit of this study is the production of 1 MW of electricity. The environmental burdens are calculated based on 1 MW of electricity from either coal firing or coal/algae cofiring. Algae replace coal in the cofiring scenario on an energy-equivalent basis (using the lower heating value).

4.3 Process Parameters

Process parameters are strongly affected by the choices made on the project-related and product-related parameters. For example, the assumption of technology bases using the latter part of the current decade justifies the targets for algae production. For the algae cofiring scenario, two algae production processes were evaluated: a direct injection process and an MEA-based process. Both processes assume algae dewatering to 50% solids using solar drying.

4.4 LCA-Specific Parameters

4.4.1 Allocation Rules

In general, the overall production of desired products generates other products, which are recovered and used in other product systems. These are considered to be coproducts. The problem is the apportioning or allocating of energy resources, raw materials, pollutants, etc. from the production steps common to the product studied and the coproducts. Inputs and outputs of the common steps can be partitioned across the coproducts on various bases, including:

- Mass
- Dry mass
- Energy content

For this analysis, there were no main processes requiring allocation.

4.5 Summary of Scoping Decisions and Approaches

Table 3 summarizes the scoping decisions and approaches used in this project.

Table 3. Summary of scoping decisions and approaches

Element	Parameter Type	Decision or Approach
<u>Project</u>	Spatial	Algae production: Southwestern United States Electricity production: United States Electricity use: Southwestern United States
	Temporal	2008
<u>Product</u>	CO ₂	Conversion to algae Venting to the atmosphere (current disposal alternative)
	Functional unit	Conversion of CO ₂ to algae to make 1 MW electricity.
<u>Process</u>	Algae cultivation and cofiring	Algae cultivation: direct injection of CO ₂ Algae cultivation: MEA extraction
	Electricity	Electricity production using coal for the United States (average)
<u>LCA</u>	Interpretation	Classification and characterization Perform sensitivity analysis, if necessary, on uncertain or variable input parameters

5 LIFE CYCLE MODELING

5.1 LCA Software

The TEAM™ software (version 3.0) developed by Ecobalance Inc. was used in this analysis.

5.2 CO₂-to-Algae Processes

The estimates of inputs and outputs for the two processes were developed using the technoeconomic model developed by Kadam and Sheehan (1996), with technology targets established for the latter part of the current decade. A simplified flow diagram is provided in Figure 4. The design basis for a 1000-hectare algal production system is shown in Table 4.

Table 4. Design parameters for algae cultivation

	Parameter	Value
Facility Parameters		
Facility size	ha	1000
Module size	ha	20
Number of modules		43
Total CO ₂ processed	mt/yr	50419
Effective culture area fraction		0.86
Biological Parameters		
Lipid content	wt. fr. dsb ^a	0.30
Protein content	wt. fr. dsb	0.32
Carbohydrate content	wt. fr. dsb	0.20
Ash content	wt. fr. dsb	0.08
Intermediate content	wt. fr. dsb	0.10
Solar radiation	kcal/m ² /d	5000
Photosynthetic efficiency	%	4.86
Salinity tolerance	g TDS/L ^b	35
Operating Parameters		
Operating season	d/yr	250
Cell concentration	g dcw/L	0.8
Residence time	d	7
Productivity	g/m ² /d	17.1
Algal production, gross	mt/y	33171
Energy of algae produced	10 ⁶ kcal/yr	173481
Downstream Processing Parameters		
Concentration factor, 1 st stage, microtrainers		10
Concentration factor, 2 nd stage, centrifuges		
Concentration factor, overall		
Harvest efficiency, overall		0.95

^aWeight fraction on dry solids basis.

^bTDS: total dissolved solids.

5.2.1 Gas Delivery

A blower is used to deliver CO₂ to ponds in the direct injection process and to an absorber in the MEA process. The MEA process also requires a smaller blower to deliver purified CO₂ gas to the ponds. Compressing CO₂ to high enough pressures to transport it for a distance is energy intensive. For transportation and nighttime storage, the compression power required is an order of magnitude higher than that for a low-pressure blower. Hence, the pond system is assumed to be near the power plant.

5.2.2 MEA Process

A detailed flow diagram for the MEA process is given by Kadam (1997). In this process, the primary pieces of equipment are the absorber and stripper columns, together with the associated piping, heat exchange, and separation equipment. The inputs and outputs were calculated based on this model.

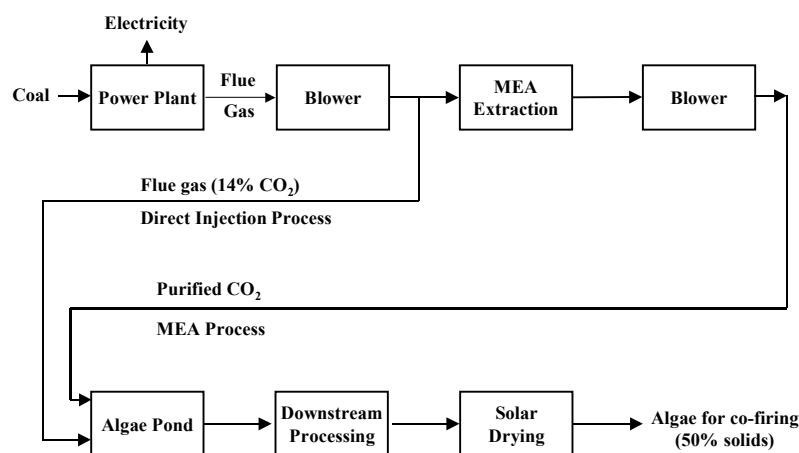


Figure 4. A simplified flow diagram for microalgae production.

5.2.3 Algae Drying

Algal drying is modeled after crop drying and dehydration practices. There is a vast experience with coffee production in Colombia using solar drying. Also, in northern Nicaragua hulled coffee is usually dried in the sun on drying floors or racks. Crop drying using the sun's energy is a centuries-old technique; however, modern solar-powered drying technologies brings new levels of cost-efficiency to the process of drying coffee, tea, cocoa, rice, corn, hay, tobacco, rubber, and a number of other crops, as well as for other agricultural dehydration processes (Brace Research Institute 1975).

Based on the agricultural experience with solar drying, it was assumed that solar drying of algae is feasible. Although a small amount of electricity may be needed for fans, no energy inputs for this step were included. The estimated power needed for fans, 5 kWh/t CO₂, <5% of total electricity, is considered to be within the margin of error of the study.

5.2.4 Data Summary for CO₂-to-Algae Processes

Based on these design parameters, the following inputs and outputs for algae cultivation can be calculated. These estimates for a 1000-hectare algal production system, using 1 MW as the basis, are reported in Table 5.

Table 5. Data summary for algae cultivation in a 1000-ha system

	Per day	Per t CO ₂
INPUTS		
Direct injection		
CO ₂ , t	680.6	1
Steam, kg	0	0
Electricity, kWh	15,100	22.2
MEA extraction		
CO ₂ , t	680.6	1
Steam, kg	1,369,570	2,010
Electricity, kWh	22,225	32.65
Algae cultivation		
NH ₃ , kg	16.85	0.025
Superphosphate, kg	12.14	0.018
Potassium sulfate, kg	9.41	0.014
CO ₂ , t	680.6	1
Steam, kg	0	0
Electricity, kWh	56,280	82.7
Algae drying		
<u>Solar drying</u>		
Steam, kg	0	0
<u>Steam drying</u>		
Steam, kg	1,615,584	2,374
OUTPUTS		
CO ₂ , kg	470	0.69
Algae – dry, kg	314,300	461.8
Algae – wet, kg	628,600	923.6
Energy of dry algae, MJ	8.12x10 ⁶	11,927

A 1000-ha algae cultivation system can process roughly 250,000 t/yr of CO₂. A 50 MW plant generates 414,000 t/yr of CO₂, which means that the 1000-ha system can use approximately 60% of the emitted CO₂. Results are provided for different levels of CO₂ recycling. However, as no compression system is assumed in the current scheme, no night storage is possible, and recycling 50% of the emitted CO₂ is assumed to be the feasible approach.

5.3 Electricity Production

The general electricity grid model includes the following:

- Pre-combustion processes: coal mining (surface and underground) and transportation; natural gas extraction and transportation; crude oil extraction (off-shore and on-shore), refining, and transportation; production of nuclear fuel (UF₆ accumulation and fuel rod manufacturing), and hydroelectric power production
- Combustion in power plants
- Distribution (losses: 7.7%)

An average situation for coal-based electricity production modeled by Ecobalance Inc. was used.

There is information available for biomass cofiring in general (Hughes 2000; Tillman, 2000a; Tillman, 2000b), however, not specifically for algae cofiring. Hence, for electricity production using algae cofiring, CO₂ and NO_x combustion-related emissions attributable to the algae were based on their carbon (56% on a dry solid basis) and nitrogen (4% on a dry solid basis) contents. About 1% of the carbon was assumed to be released as CO. Electricity production from algae was assumed at 33% efficiency and was based on the net energy available after evaporating the water. Electricity production from algae depended on the extent of CO₂ recycle; the remainder was from coal.

5.4 Steam Production

The energy necessary to convert water to steam is based on the enthalpy of the steam (2.6 MJ/kg at approximately 150 psi and 350°F) and a boiler efficiency of 80%. Steam is assumed to be produced by combusting fuel in industrial boilers. The fuel can consist of coal, natural gas or heavy fuel oil.

The assumed heating values of the three fuels are as follows:

- Natural Gas – 52 MJ/kg
- Heavy Fuel Oil – 42 MJ/kg
- Coal – 29.3 MJ/kg

The emission factors for industrial boilers were obtained from the AP-42 report by the EPA (EPA 1995b). These numbers were compared with a study done by the Argonne National Laboratory (Wang 1996), to verify and expand on the EPA emission factors.

Specifically, a coal-fired boiler was modeled in this study. All the factors reported are for uncontrolled emissions. If control technologies are used, the emission factors should be reduced by the efficiencies of the control devices. Emission factors for heavy fuel oil and natural gas production are outlined by Kadam et al. (1999).

5.5 CO₂ Accounting

For this study, it is assumed that CO₂ released during algae cofiring is recycled and is reused by the algae (see Figure 3). Thus, the net CO₂ balance for growing and burning of algae is zero. Therefore, algae-derived CO₂ is not used in the impact assessment phase to calculate greenhouse gas potential. During algae cultivation, however, some fossil energy is consumed, and the resultant fossil CO₂ is charged to the algae scenario as a burden.

6 DATA QUALITY AND SOURCES

For an LCA, there are two different types of data: primary and secondary (SETAC 1993). Primary data are obtained directly from individual production plants or companies. Secondary data are published sources such as databases, industry or government publications, journals, or books. Another kind of secondary data includes “educated guesses,” or data coming from experts based on their knowledge in the field, but not published.

In general, the goals for data collection, quality, and utilization are to use the most recent data available that are representative of an industry or practice. The specific goals for this study were to obtain data on the processes leading to the conversion of CO₂ into algal mass and its cofiring with coal to produce electricity.

6.1 Data Sources

Details of the data used in the analysis are summarized in Table 5.

6.2 Data Quality

Data in an LCA should have indicators for reliability and completeness. The “reliability indicator” pertains to how data were obtained and verified, independent of the data quality goals outlined in the study. The “completeness indicator” pertains to how representative the data samples are, i.e., do the data represent an adequate sample size, and do the data cover an adequate period such that normal fluctuations are evened out? The completeness indicator is also treated as independent of the data quality goals outlined in the study. Currently, actual data indicators have not been established in LCA guidelines. Instead, a table is generally provided to indicate the type of data in each life cycle sector and the reliability and completeness for each. Table 6 provides the general data categories in this study and provides a description of each. In addition, Table 6 lists the sources and whether they are primary or secondary, a “checklist” of the reliability criteria, the geographical and temporal extent of the data, and limitations.

Table 6. Data sources and quality

Data Category	Description	Source Type and Date	Geographic and Temporal Representation	Reliability and Completeness
Algae production	Materials, energy, emissions	Primary; NREL (1999)	U.S. 1990s	Reliable and complete (based on bench-scale data and process modeling)
Electricity production	Materials, energy, emissions	Secondary	U.S. 1990s	Reliable and complete
Steam production	Materials, energy, emissions	Secondary; U.S. EPA AP-42 (1997)	U.S. 1980s, 1990s	Reliable and complete
Algae cofiring	Materials, energy, emissions	N/A		Energy values: Reliable and complete Emissions: Assumed but considered to be a reliable approximation

7 RESULTS AND DISCUSSION

7.1 Presentation of Results

The results are presented for the two different scenarios: 1) venting of CO₂ and coal firing (*status quo*) and 2) converting CO₂ to algae and its cofiring. As mentioned earlier, the basis chosen for the comparison of the two different disposal options is 1 MW of electricity. In addition to actual flows, percentage differences are also included, which indicate the degree to which the values for the algae cofiring scenario (Scenario 2) were different from those for the *status quo* scenario (Scenario 1). A positive value indicates the percentage by which the values for the algae cofiring scenario were lower than those for the coal-firing scenario, and vice versa.

$$\% \text{ Difference} = \frac{\text{Scenario 1 value} - \text{Scenario 2 value}}{\text{Scenario 1 value}} \times 100$$

7.2 Time-Space Implications of Emissions

It should be noted that this report shows the life-cycle emissions of the two options without considering the spatial and temporal attributes, meaning that the results are aggregated over different locations and different time frames. This report only shows the difference in the total emissions of the two options and does not account for concentrations of pollutants at a given time.

7.3 Life Cycle Energy Balance

The energy use of the competing scenarios is one measure of their overall environmental performance. LCIs provide an opportunity to quantify both the total energy demands and the overall energy efficiencies of processes and products. In this study, several different types of energy flows are tracked through each life cycle. For clarity, each of these energy flows is defined below.

- *Total Primary Energy.* All raw materials extracted from the environment can contain² energy. In estimating the total primary energy inputs to each life cycle, the cumulative energy content of all resources extracted from the environment is considered.
- *Feedstock Energy.* Energy contained in raw materials that end up directly in the final product is termed “feedstock energy.” Feedstock energy is a subset of primary energy inputs.
- *Process Energy.* The second major subset of primary energy is “process energy.” This is limited to energy inputs in the life cycle exclusive of the energy contained in the feedstock (as defined in the previous bullet). It is the energy contained in raw materials extracted from the environment that does not contribute to the energy of the product itself, but is needed to process feedstock energy into its final product form. Process energy is primarily generated from coal, natural gas, uranium, and hydroelectric power consumed directly or indirectly in the product life cycle.
- *Fossil or Nonrenewable Energy.* The primary energy that comes from fossil sources specifically (coal, oil, and natural gas) is tracked because it is important to distinguish between fossil and non-fossil energy. All three of the previously defined energy flows can be categorized as either fossil or non-fossil energy.
- *Renewable Energy.* Renewable energy refers to energy obtained from algae and also to electricity production from renewable sources such as biomass and hydroelectricity.

In the summary tables, the following energy values are reported: 1) feedstock energy, 2) fossil or nonrenewable energy, 3) renewable energy, 4) process energy, and 5) total primary energy. Criteria air pollutants are linked to the use of both nonrenewable and renewable energy, whereas natural resource depletion³ and fossil CO₂ emissions are only linked to nonrenewable sources. Renewable energy use in Scenario 1 refers to renewable resources used to produce a portion of electricity used. Process energy indicates the net energy input to the process and can be useful in comparing process options.

² The energy “contained” in a raw material is the amount of energy that would be released by the complete combustion of that raw material. This “heat of combustion” can be measured in two different ways: as a higher heating value or a lower heating value. Combustion results in the formation of CO₂ and water. Higher heating values consider the amount of energy released when the final combustion products are gaseous carbon dioxide and liquid water. Lower heating values take into account the loss of energy associated with the vaporization of the liquid water combustion product. The energy content used is based on the lower heating values for each material.

³ Soil erosion is not included in the calculation of natural resource depletion because data were not available. The effects of biomass harvesting on soil erosion are more difficult to quantify than the removal of other natural resources, e.g., coal and oil.

7.4 LCI for Coal Firing versus Coal/Algae Cofiring: Direct Injection Process

A comparison of environmental flows for Scenario 2 versus Scenario 1 for the direct injection process (using solar drying) is presented in Table 7. Table 7 lists results for 100%, 75%, 50%, and 25% CO₂ recycle, and Figures 5 through 18 provide results in graphical form for 100% and 50% CO₂ recycle. However, 50% CO₂ recycle is the most feasible, and the following discussion is limited to this option.

7.4.1 Resource Depletion

Depletion of non-renewable resources, such as coal, crude oil, and natural gas, is an important sustainability criterion. Coal usage is significantly lower but natural gas and oil usage are higher for Scenario 2. The reason that natural gas usage is higher for Scenario 2 is because of the ammonia and super phosphate use during algae production, which is absent in Scenario 1. Super phosphate production also consumes a fair amount of crude oil. Thus, the algae option offsets coal consumption but other non-renewable resources are consumed in its production. The relative importance of depleting these non-renewable resources is also captured in impact assessment (see section 7.7).

7.4.2 Air Pollutants

Carbon monoxide and hydrocarbons (except methane) emissions for Scenario 2 are somewhat higher, by 6%–8%, than those for Scenario 1. This increase can be considered as not significant as it falls within the margin of error for the analysis. However, this increase results from the higher natural gas and ammonia consumption for Scenario 2 (see Table 8). Particulate emissions (PM₁₀ and unspecified), SO_x, and NO_x are lower for Scenario 2 by 39% each. Coal production and electricity from coal both result in higher particulates, SO_x, and NO_x emissions. These three emissions are lower for Scenario 2 because it partly displaces coal production and electricity from coal.

7.4.3 Waste Generation

In case of liquid phase wastes, COD values are significantly higher for Scenario 2. This is a result of high COD values attributable to fertilizer production. However, these water emissions do not occur during the actual process, but rather during upstream production of raw materials used in the process, e.g., ammonia, super phosphate, potassium sulfate, etc. As shown in Table 8, COD values are especially high for ammonia, which is used only in Scenario 2. Total solid waste values are slightly lower for Scenario 2 than those for Scenario 1. These can be attributed to much lower coal requirements for Scenario 2.

7.4.4 Energy Consumption and GHGs

Process energy requirements are comparable for both the scenarios. This means that the energy input to the algae production step is comparable to that of the coal production step. However, the nature of the energy consumed is different. Nonrenewable energy consumption is 34% lower for Scenario 2 than for Scenario 1, and as expected, the renewable energy consumption is very high for Scenario 2 and very low for Scenario 1. Emissions are lower by 30-40% for CO₂, N₂O, and CH₄, which are key GHGs. This is due to the high emissions of these gases during coal production and electricity generation from coal (Table 9).

Table 7. Life cycle inventory for coal firing versus coal/algae cofiring: Direct injection process (solar drying)

		Base case	100% CO₂ recycle		75% CO₂ recycle		50% CO₂ recycle		25% CO₂ recycle	
		<i>Flow value</i>	<i>Flow value</i>	<i>Difference, %</i>	<i>Flow value</i>	<i>Difference, %</i>	<i>Flow value</i>	<i>Difference, %</i>	<i>Flow value</i>	<i>Difference, %</i>
Natural resources										
Coal	t	4,083	704	83	1,549	62	2,394	41	3,239	21
Natural gas	kg	23	318	-1,316	244	-987	170	-658	97	-329
Oil	t	28	91	-221	75	-166	59	-111	44	-55
Air emissions										
Carbon dioxide	t	7,943	2,049	74	3,522	56	4,996	37	6,469	19
Carbon monoxide	kg	2,056	2,289	-11	2,230	-8	2,172	-6	2,114	-3
Hydrocarbons (except methane)	kg	498	574	-15	555	-11	536	-8	517	-4
Methane	kg	18.1	7.6	58	10.2	44	12.8	29	15.5	15
Nitrogen oxides	kg	37	8.2	78	15.4	58	22.6	39	29.8	19
Nitrous oxide	kg	231	49	79	95	59	140	39	186	20
Particulates (PM 10)	g	9.6	2.2	77	4.0	58	5.9	39	7.8	19
Particulates (unspecified)	kg	47	10	78	19	59	28	39	37	20
Sulfur oxides	t	67	22.4	66	33.5	50	44.5	33	55.6	17
Waste										
COD (Chemical Oxygen Demand)	kg	60.0	728	-1,115	561	-836	394	-557	227	-279
Solid waste (total)	t	2,148	1,530	29	1,684	22	1,839	14	1,994	7
Energy										
Feedstock energy	MJ	108,953	4.6x10 ⁶	-4,129	3.5x10 ⁶	-3,097	2.4x10⁶	-2,065	1.2x10 ⁶	-1,032
Non-renewable energy	MJ	1.2x10 ⁸	4.0x10 ⁷	68	6.0x10 ⁷	51	8.0x10⁷	34	1.0x10 ⁸	17
Renewable energy	MJ	41,007	9.3x10 ⁷	NM ^a	7.0x10 ⁷	NM ^a	4.6x10⁷	NM^a	2.3x10 ⁷	NM ^a
Total primary energy	MJ	1.22x10 ⁸	1.32x10 ⁸	-8	1.3x10 ⁸	-6	1.27x10⁸	-4	1.25x10 ⁸	-2
Process energy	MJ	1.2x10 ⁸	1.3x10 ⁸	-4	1.3x10 ⁸	-3	1.2x10⁸	-2	1.2x10 ⁸	-1

^aNot meaningful to report.

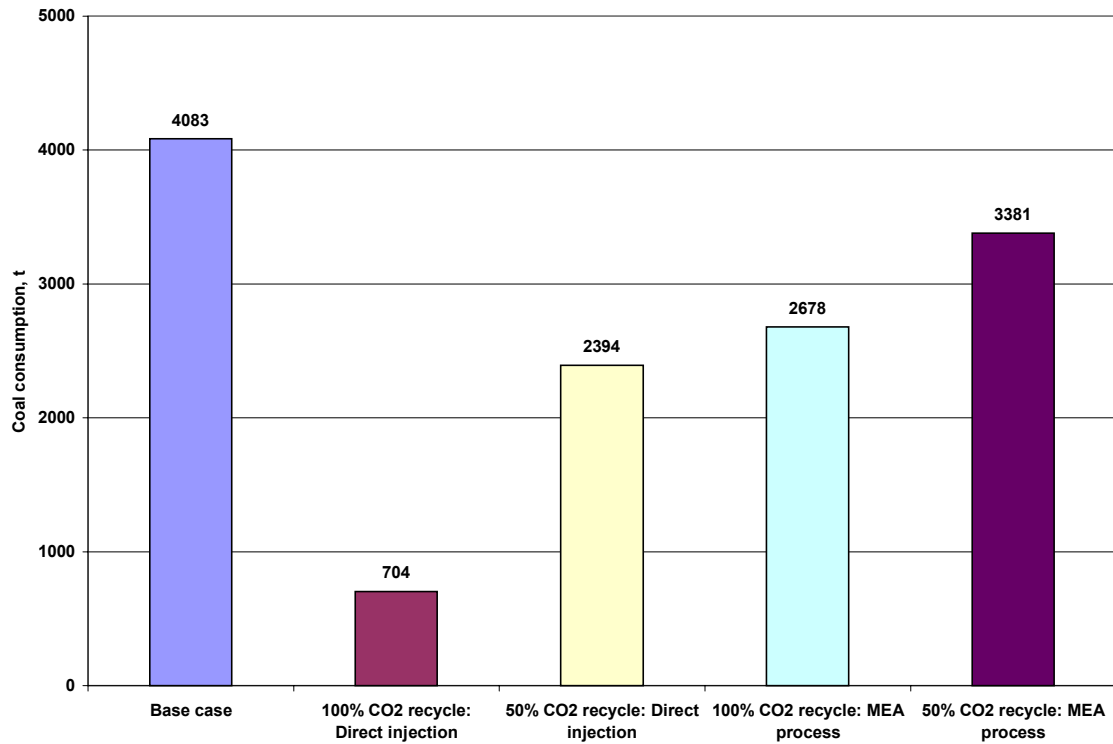


Figure 5. Coal usage for coal firing versus coal/algae cofiring.

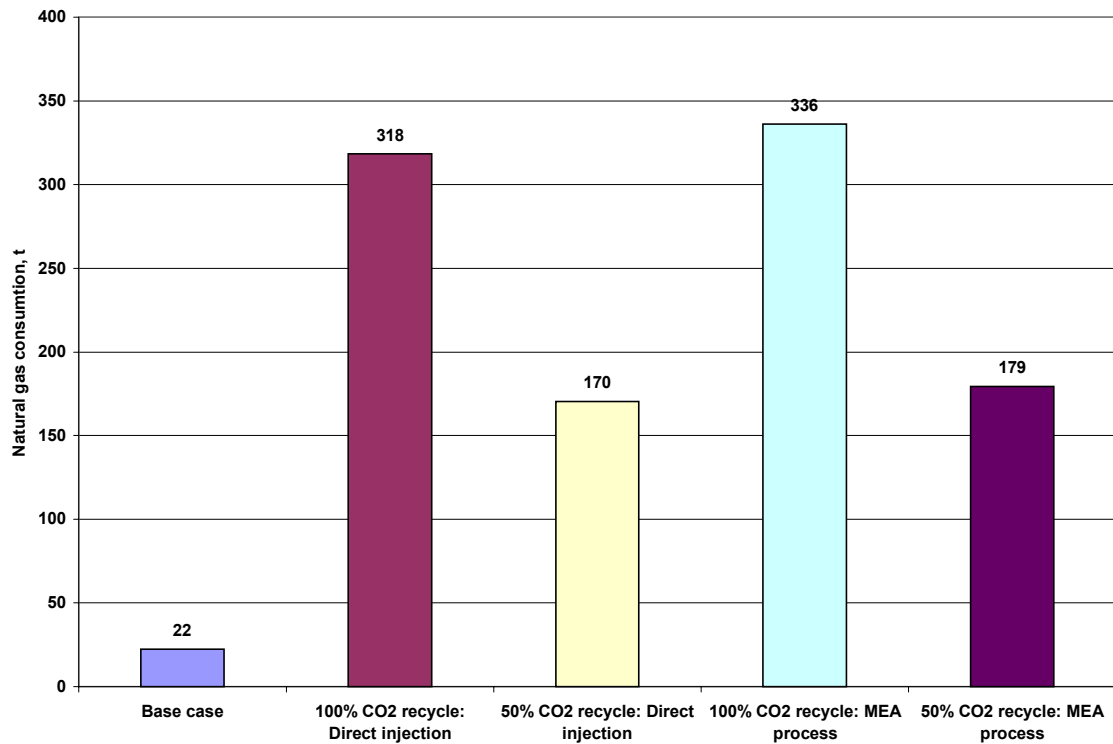


Figure 6. Natural gas usage for coal firing versus coal/algae cofiring.

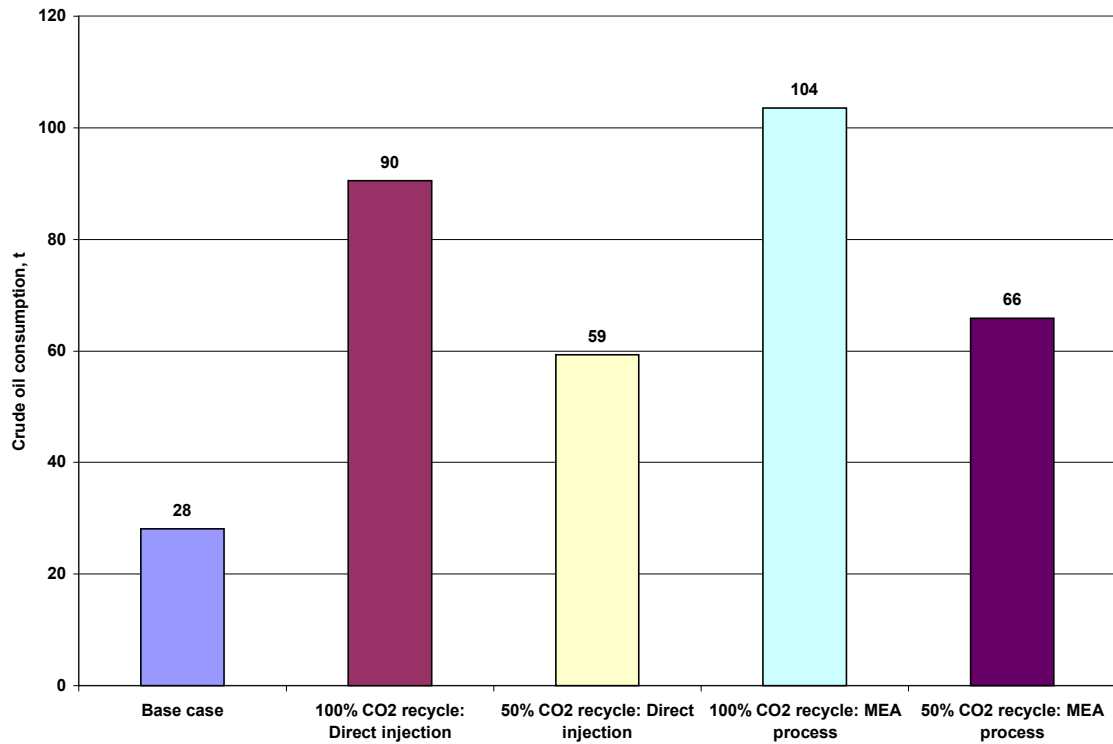


Figure 7. Crude oil usage for coal firing versus coal/algae cofiring.

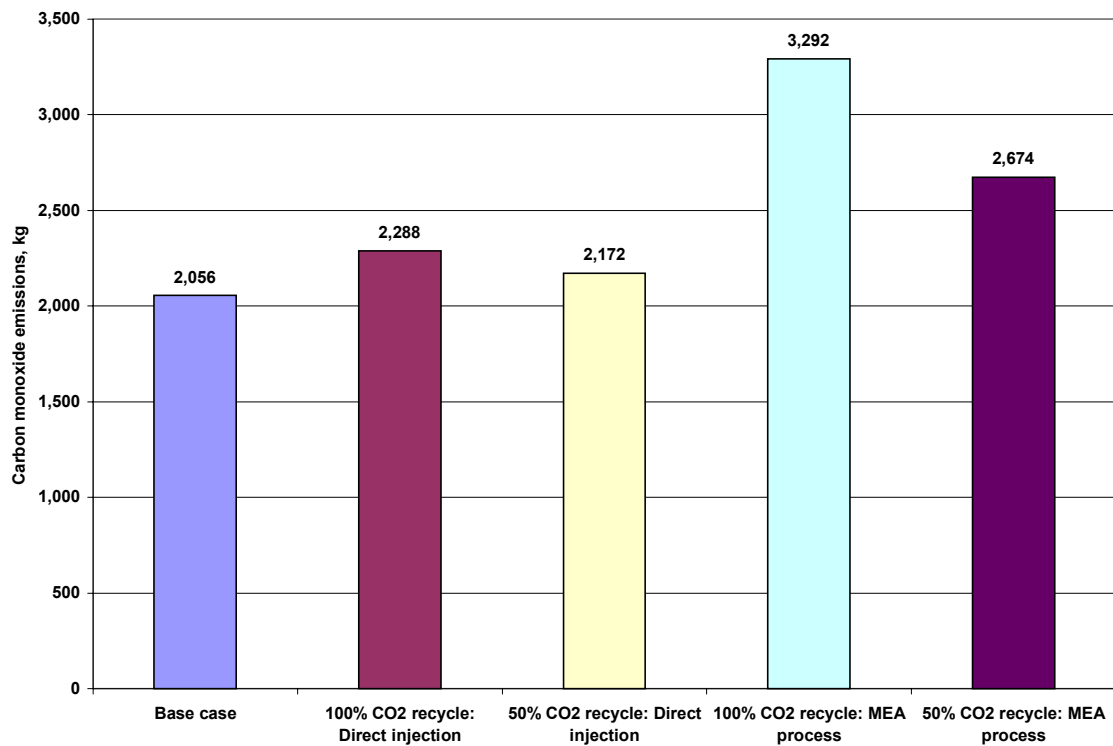


Figure 8. Carbon monoxide emissions for coal firing versus coal/algae cofiring.

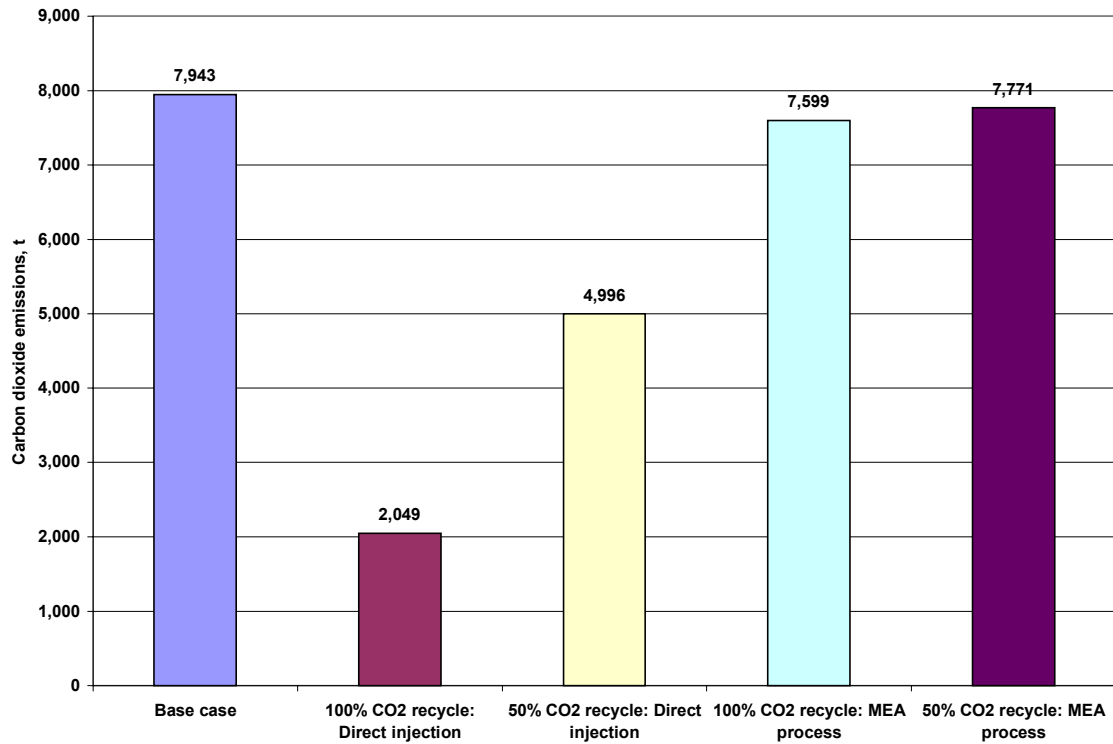


Figure 9. Fossil CO₂ emissions for coal firing versus coal/algae cofiring.

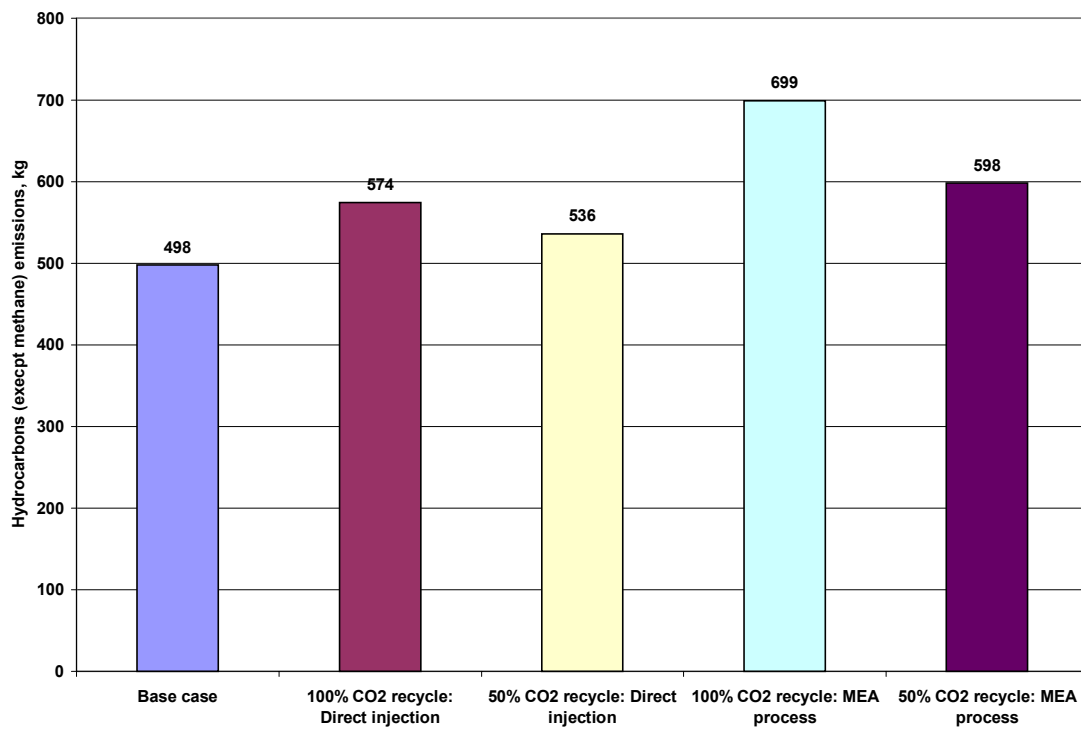


Figure 10. Hydrocarbon (except methane) emissions for coal firing versus coal/algae cofiring.

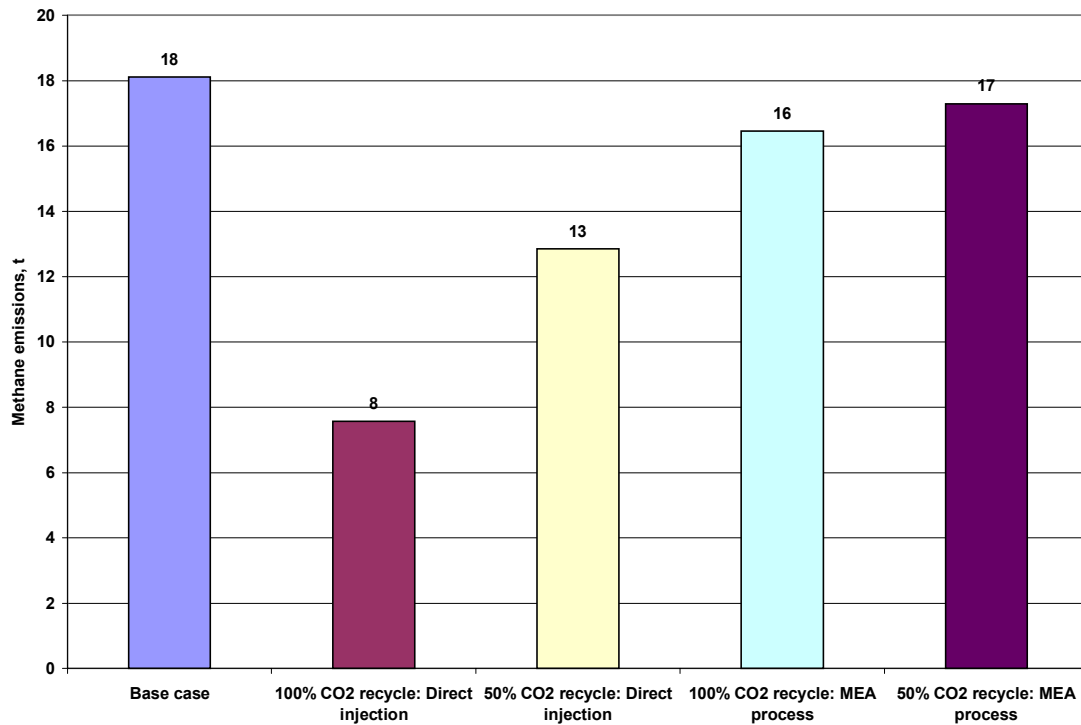


Figure 11. Methane emissions for coal firing versus coal/algae cofiring.

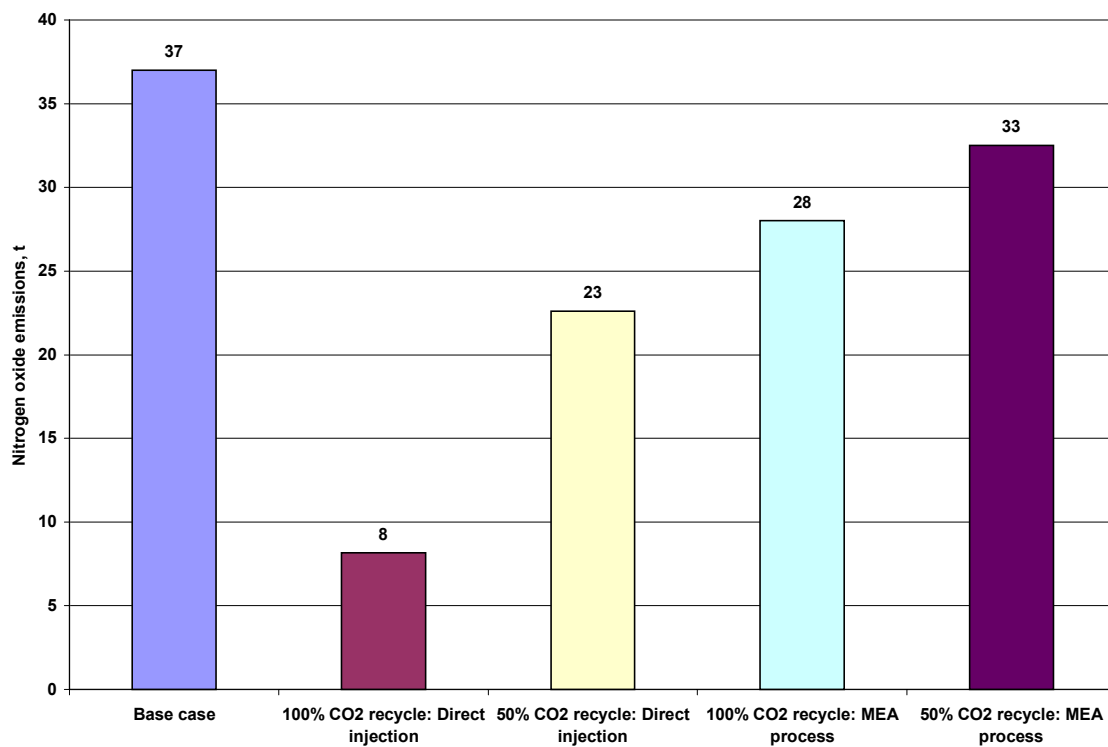


Figure 12. Nitrogen oxides (NO_x as NO₂) emissions for coal firing versus coal/algae cofiring.

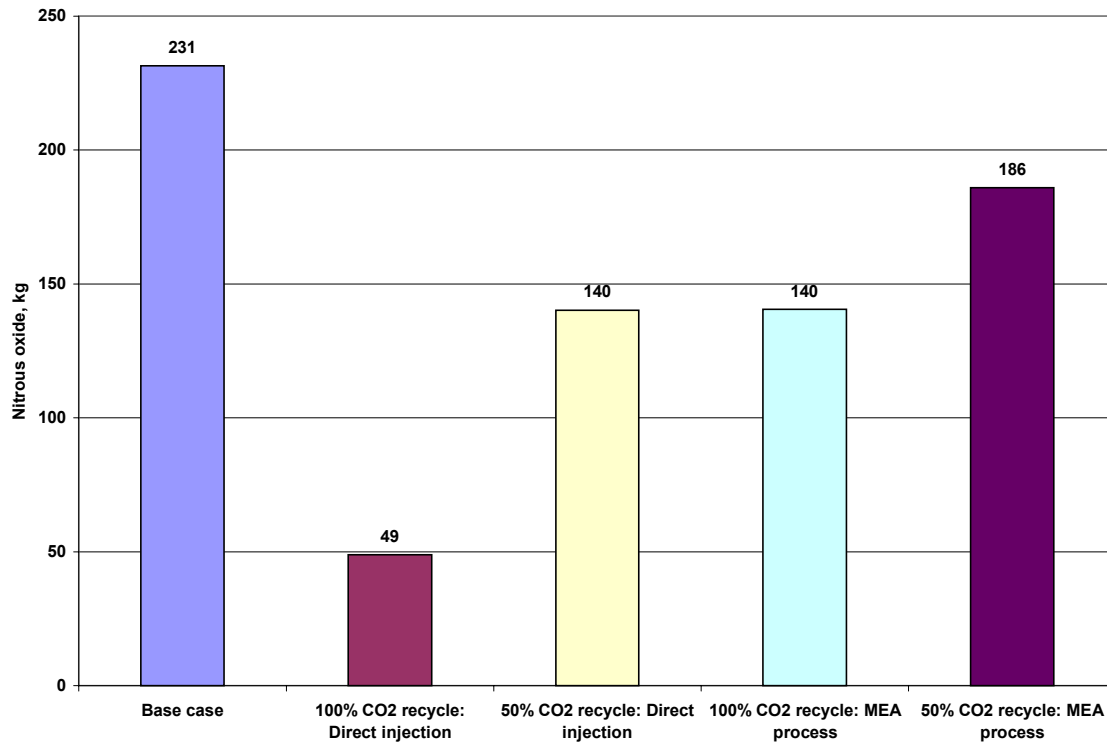


Figure 13. Nitrous oxide emissions for coal firing versus coal/algae cofiring.

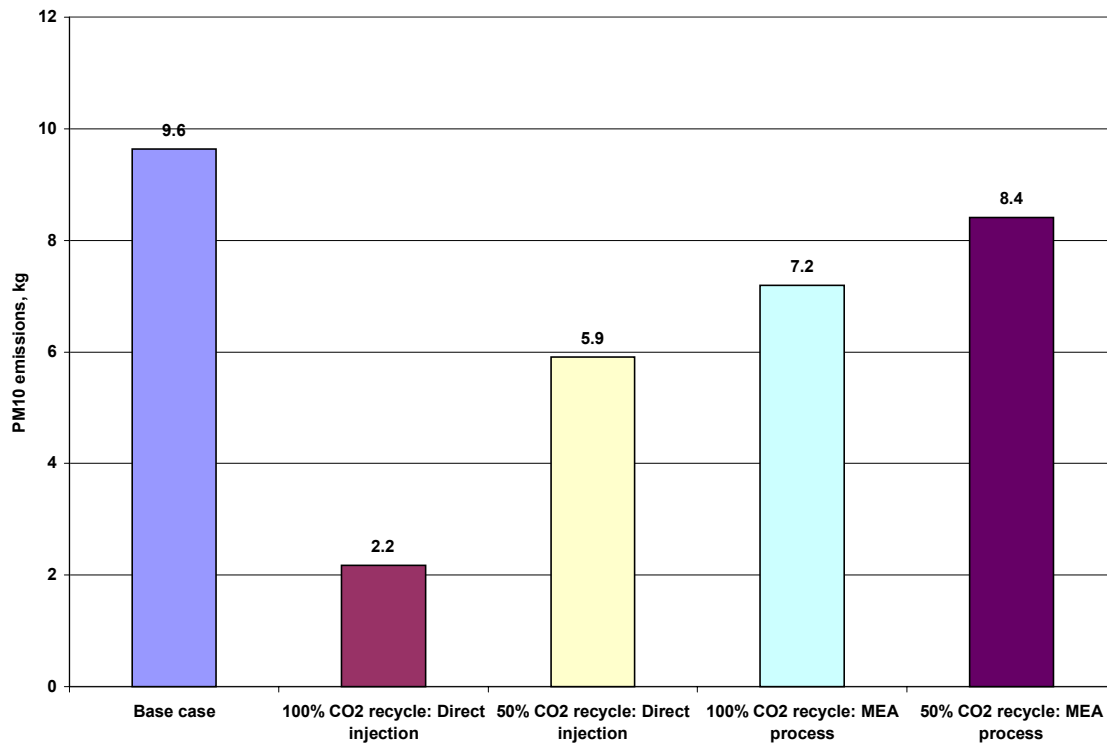


Figure 14. PM10 emissions for coal firing versus coal/algae cofiring.

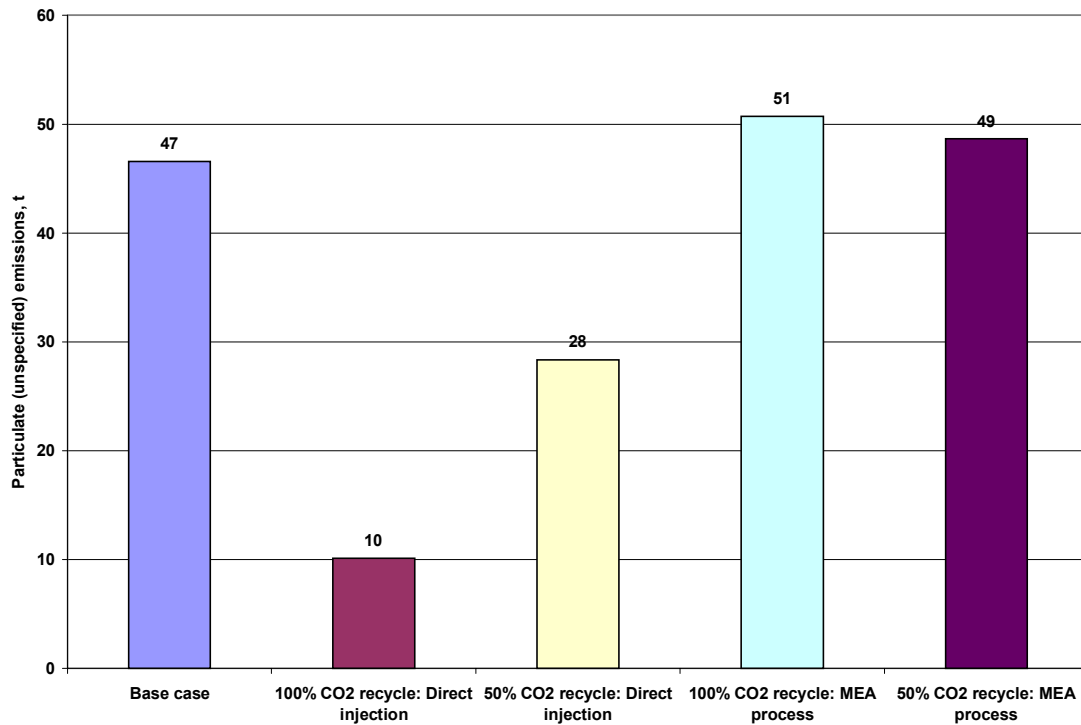


Figure 15. Particulate matter (unspecified) emissions for coal firing versus coal/algae cofiring.

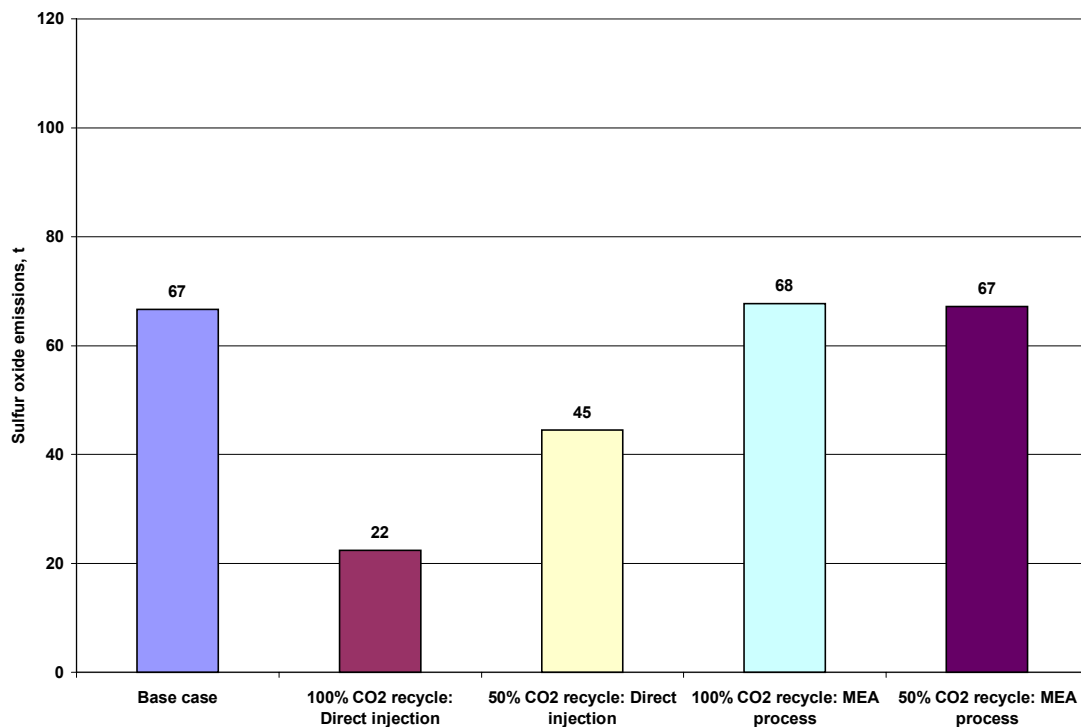


Figure 16. Sulfur oxides (SO_x as SO_2) emissions for coal firing versus coal/algae cofiring.

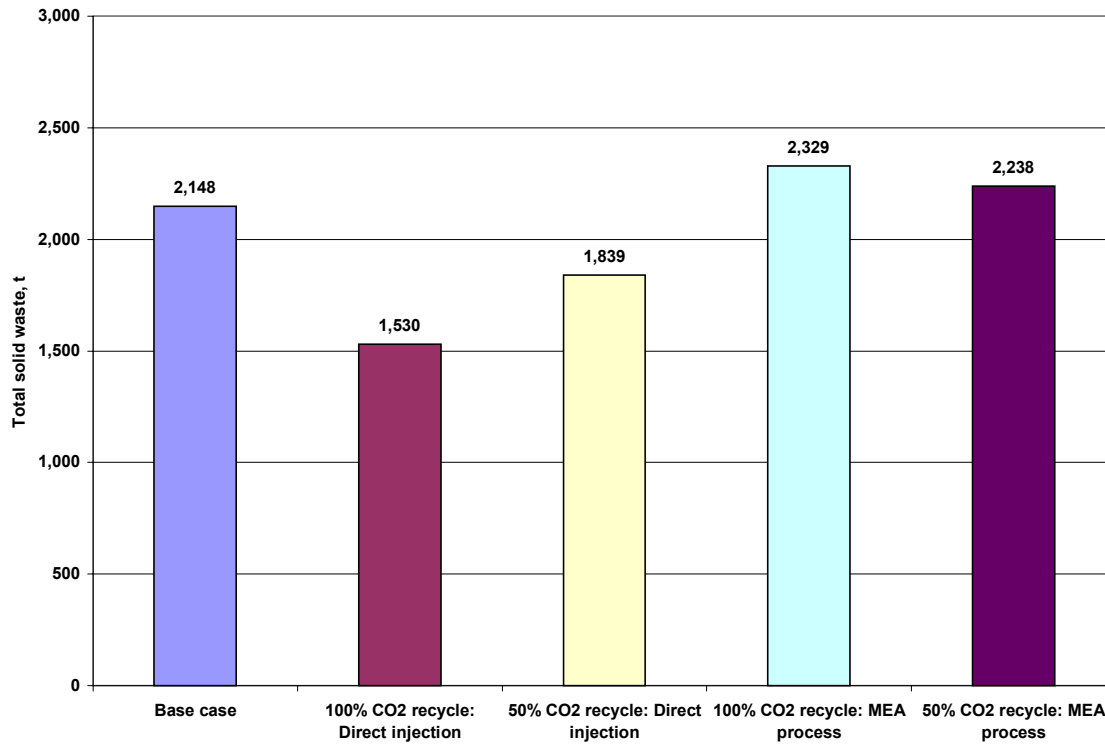


Figure 17. Total solid waste produced for coal firing versus coal/algae cofiring.

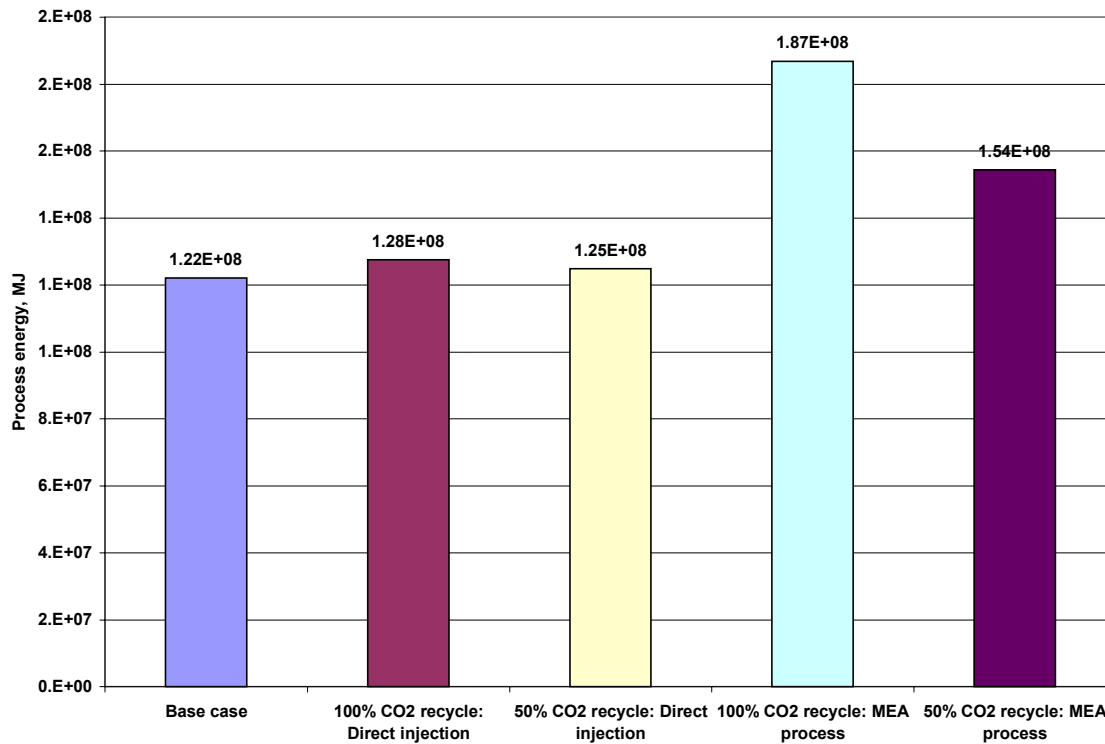


Figure 18. Process energy required for coal firing versus coal/algae cofiring.

Table 8. Key environmental flows for selected modules: non-renewable resource consumption, air emissions, and waste generation

	Basis	Coal, kg	Natural gas, kg	Oil, kg	CO, g	Hydro-carbons, g	Total solid waste, kg	COD, g
Ammonia	1 kg	0.073	0.93	0.005	9.7	0.63	0.38	3.72
Super phosphate	1 kg	0.001	0.96	0.63	0.41	2.6	7.35	0.02
Potassium sulfate	1 kg	-0.09	0.022	-0.022	0.27	0.06	0.64	0.0037
Coal	1 kg	1.009	~0	0.006	0.2	0.04	0.28	0.014
Natural gas	1 kg		1.22		1.83	0.82		0.0117
Steam (coal)	28 MJ	1.0	0	0	0.3	0.016	0.0825	0.002
Electricity (coal)	1 MJ	0.136	~0	~0	0.04	0.01	0.034	~0

Table 9. Key environmental flows for selected modules: GHG emissions

	Basis	Carbon Dioxide, g	Methane	Nitrous Oxide
Ammonia	1 kg	2655	14	0.03
Super phosphate	1 kg	1575	12.7	0.02
Potassium sulfate	1 kg	-370	0.06	0.005
Coal	1 kg	40.5	4.4	0.007
Natural gas	1 kg	476	18	0.004
Steam (coal)	28 MJ	2786	0.02	0.04
Electricity (coal)	1 MJ	367	0.013	0.007

7.5 LCI for Coal Firing versus Coal/Algae Cofiring: MEA Process

A comparison of environmental flows for Scenario 2 versus Scenario 1 for the MEA process (using solar drying) is shown in Table 10. Again this table shows values for 100%, 75%, 50%, and 25% recycle, and as the 50% recycle option is the most realistic, the following discussion is limited to this option.

Table 10. Life cycle inventory for coal firing versus coal/algae cofiring: MEA Process (solar drying)

			Base case		100% CO ₂ recycle		75% CO ₂ recycle		50% CO ₂ recycle		25% CO ₂ recycle	
			Flow value		Flow value Difference, %		Flow value Difference, %		Flow value Difference, %		Flow value Difference, %	
Natural resources												
Coal	t	4,083			2,678	34	3,030	26	3,381	17	3,732	9
Natural gas	kg	23			336	-1395	258	-1046	179	-698	101	-349
Oil	t	28			104	-268	85	-201	66	-134	47	-67
Air emissions												
Carbon dioxide	t	7,943			7,599	4	7,685	3	7,771	2	7,857	1
Carbon monoxide	kg	2,056			3,292	-60	2,983	-45	2,674	-30	2,365	-15
Hydrocarbons (except methane)	kg	498			699	-40	649	-30	598	-20	548	-10
Methane	kg	18.1			16	9	17	7	17	5	18	2
Nitrogen oxides	kg	37			28	24	30	18	33	12	35	6
Nitrous oxide	kg	231			140	39	163	29	186	20	209	10
Particulates (PM 10)	g	9.6			7	25	8	19	8	13	9	6
Particulates (unspecified)	kg	47			51	-9	50	-7	49	-4	48	-2
Sulfur oxides	t	67			68	-2	67	-1	67	-1	67	0
Waste												
COD (Chemical Oxygen Demand)	kg	60.0			757	-1,164	583	-873	409	-582	234	-291
Solid waste (total)	t	2,148			2,329	-8	2,284	-6	2,238	-4	2,193	-2
Energy												
Feedstock energy	MJ	108,953			4.8x10 ⁶	-4,260	3.6x10 ⁶	-3,195	2.4x10 ⁶	-2130	1.3x10 ⁶	-1,065
Non-renewable energy	MJ	1.2x10 ⁸			9.8x10 ⁷	18	1 x10 ⁸	14	1.1x10 ⁸	9	1.15x10 ⁸	5
Renewable energy	MJ	41,007			9.3x10 ⁷	NM ^a	7x10 ⁷	NM ^a	4.6x10 ⁷	NM ^a	2.3x10 ⁷	NM ^a
Total primary energy	MJ	1.22x10 ⁸			1.9x10 ⁸	-57	1.7x10 ⁸	-43	1.6x10 ⁸	-28	1.4x10 ⁸	-14
Process energy	MJ	1.22x10 ⁸			1.9x10 ⁸	-53	1.7x10 ⁸	-40	1.5x10 ⁸	-27	1.38x10 ⁸	-13

^aNot meaningful to report.

7.5.1 Resource Depletion

As in the case of the direct injection process, coal consumption is lower but natural gas and oil usage is higher for Scenario 2. The percent increase of natural gas and oil usage is about the same as for the direct injection process since these are mainly consumed during algae cultivation, which is common to both the processes. The percent decrease for coal consumption is lower compared to the direct injection process because of higher steam requirements during MEA extraction.

7.5.2 Air Pollutants

Carbon monoxide and hydrocarbons (except methane) emissions for Scenario 2 are higher, by 28% and 17%, respectively, than those for Scenario 1. These can be attributed to the higher steam consumption for the MEA process.

7.5.3 Waste Generation

COD values are again considerably higher. The percent increase is about the same as for the direct injection process given that the fertilizers are consumed during algae cultivation at the same rate for both the processes. Total solid waste values are comparable for both the scenarios. The increase in total solid waste compared to the direct injection process stems from higher steam consumption in the MEA process.

7.6 Sensitivity Analysis on Drying Processes

Solar drying was assumed as a base case scenario. Although this is considered to be a technically feasible approach, a sensitivity analysis on using steam drying was conducted to illustrate the impact of using extra energy for algae drying. A comparison of environmental flows for Scenario 2 versus Scenario 1 using steam drying is shown in Table 11 for the direct injection process and in Table 12 for the MEA process. As expected, the environmental flows related to coal production are higher and the benefits, such as GHG reduction, are lower. Hence, this option would not be a feasible one either from economic or environmental standpoint.

7.7 LCIA for Coal Firing versus Coal/Algae Cofiring

In addition to the environmental flows, impact indicator values were also calculated for the above scenarios (using solar drying). These indicators are used to give a broader insight into the environmental impacts of the competing scenarios by examining the potential impacts beyond the initial release. The indices calculated are greenhouse potential, natural resources depletion, and acidification potential and eutrophication potential (see Appendix B for definitions).

It is evident from Table 13 and Table 14 that for greenhouse potential and acidification potential, Scenario 1 is worse than Scenario 2, using either of the production schemes. The differences between the two scenarios for the MEA process are, however, not significant. The lower greenhouse potential is mainly because of the CO₂ recycle in Scenario 2. Also, the displacement of coal accrues lower CO₂, SO_x, and NO_x emissions, which coal power plants generate in large amounts. Figures 19 through 22 also graphically depict these environmental impacts.

Table 11. Life cycle inventory for coal firing versus coal/algae cofiring: Direct injection process (steam drying)

			Base case		100% CO ₂ recycle		75% CO ₂ recycle		50% CO ₂ recycle		25% CO ₂ recycle		
			Flow value		Flow value Difference, %		Flow value Difference, %		Flow value Difference, %		Flow value Difference, %		
Natural resources													
Coal	t	4,083		2,657	35		3,014	26	3,370	17		3,727	9
Natural gas	kg	23		337	-1,397		258	-1,048	180	-698		101	-349
Oil	t	28		103	-267		85	-201	66	-134		47	-67
Air emissions													
Carbon dioxide	t	7,943		7,668	3		7,737	3	7,805	2		7,874	1
Carbon monoxide	kg	2,056		3,282	-60		2,975	-45	2,669	-30		2,362	-15
Hydrocarbons (except methane)	kg	498		689	-38		641	-29	593	-19		546	-10
Methane	kg	18.1		16	10		17	7	17	5		18	2
Nitrogen oxides	kg	37		28	25		30	18	32	12		35	6
Nitrous oxide	kg	231		138	40		161	30	185	20		208	10
Particulates (PM 10)	g	9.6		7	26		8	19	8	13		9	6
Particulates (unspecified)	kg	47		52	-11		50	-8	49	-5		48	-3
Sulfur oxides	t	67		68	-2		68	-2	67	-1		67	-1
Waste													
COD (Chemical Oxygen Demand)	kg	60.0		757	-1163		583	-873	408	-582		234	-291
Solid waste (total)	t	2,148		2,302	-7		2,264	-5	2,225	-4		2,187	-2
Energy													
Feedstock energy Non-renewable	MJ	108,953		4.8x10 ⁶	-4,265		3.6x10 ⁶	-3,199	2.4x10 ⁶	-2,133		1.3x10 ⁶	-1066
Renewable energy	MJ	1.2x10 ⁸		9.8x10 ⁷	19		1.04 x10 ⁸	14	1.09x10 ⁸	9		1.15x10 ⁸	5
Total primary energy	MJ	41,007		9.3x10 ⁷	NM ^a		7.0x10 ⁷	NM ^a	4.6x10 ⁷	NM ^a		2.3x10 ⁷	NM ^a
Process energy	MJ	1.22x10 ⁸		1.91x10 ⁸	-56		1.74x10 ⁸	-42	1.57x10 ⁸	-28		1.39x10 ⁸	-14
	MJ	1.22x10 ⁸		1.86x10 ⁸	-53		1.7x10 ⁸	-39	1.54x10 ⁸	-26		1.38x10 ⁸	-13

^aNot meaningful to report.

Table 12. Life cycle inventory for coal firing versus coal/algae cofiring: MEA process (steam drying)

			Base case		100% CO ₂ recycle		75% CO ₂ recycle		50% CO ₂ recycle		25% CO ₂ recycle		
			Flow value		Flow value Difference, %		Flow value Difference, %		Flow value Difference, %		Flow value Difference, %		
Natural resources													
Coal	t	4,083		4,631	-13		4,494	-10	4,357	-7		4,220	-3
Natural gas	kg	23		355	-1,476		271	-1,107	188	-738		105	-369
Oil	t	28		117	-314		94	-235	72	-157		50	-78
Air emissions													
Carbon dioxide	t	7,943		13,218	-66		11,899	-50	10,581	-33		9262	-17
Carbon monoxide	kg	2,056		4,285	-108		3,728	-81	3,170	-54		2,613	-27
Hydrocarbons (except methane)	kg	498		813	-63		734	-47	656	-32		577	-16
Methane	kg	18.1		25	-39		23	-30	22	-20		20	-10
Nitrogen oxides	kg	37		48	-29		45	-22	42	-15		40	-7
Nitrous oxide	kg	231		230	1		230	1	230	0		231	0
Particulates (PM 10)	g	9.6		12	-26		12	-20	11	-13		10	-7
Particulates (unspecified)	kg	47		92	-98		81	-74	69	-49		58	-25
Sulfur oxides	t	67		114	-70		102	-53	90	-35		78	-18
Waste													
COD (Chemical Oxygen Demand)	kg	60.0		787	-1,213		605	-910	423	-606		242	-303
Solid waste (total)	t	2,148		3,101	-44		2,863	-33	2,625	-22		2,386	-11
Energy													
Feedstock energy	MJ	108,953		4.9x10 ⁶	-4,396		3.7x10 ⁶	-3,297	2.5x10 ⁶	-2,198		1.3x10 ⁶	-1,099
Non-renewable energy	MJ	1.2x10 ⁸		1.57x10 ⁸	-30		1.48x10 ⁸	-23	1.39x10 ⁸	-15		1.3x10 ⁸	-8
Renewable energy	MJ	41,007		9.3x10 ⁷	NM ^a		7.0x10 ⁷	NM ^a	4.6x10 ⁷	NM ^a		2.3x10 ⁷	NM ^a
Total primary energy	MJ	1.22x10 ⁸		2.5x10 ⁸	-105		2.18x10 ⁸	-79	1.86x10 ⁸	-52		1.54x10 ⁸	-26
Process energy	MJ	1.22x10 ⁸		2.46x10 ⁸	-101		2.15x10 ⁸	-76	1.84x10 ⁸	-51		1.53x10 ⁸	-25

^aNot meaningful to report.

Table 13. Life cycle impact assessment for coal firing versus coal/algae cofiring: Direct injection process (solar drying)

Impact indices	Base case	100% CO ₂ recycle		50% CO ₂ recycle	
	<i>Index value</i>	<i>Index value</i>	<i>Difference, %</i>	<i>Index value</i>	<i>Difference, %</i>
IPCC-Greenhouse effect t CO ₂ (100 years) ^a	8,460	2,248	73	5,354	37
CML-Air acidification ^b t H ⁺	3.0	0.9	69	1.9	35
CML- Depletion of nonrenewable resources ^b	1.7x10 ⁻¹⁵	4.13x10 ⁻¹⁴	-2,301	2.15x10⁻¹⁴	-1,151
CML-Eutrophication t PO ₄	4.9	16.2	-232	10.5	-116

^aIPCC = Intergovernment Panel on Climate Change, United Nations.

^bCML = Centre of Environmental Science, Leiden University, The Netherlands.

Table 14. Life cycle impact assessment for coal firing versus coal/algae cofiring: MEA process (solar drying)

Impact indices	Base case	100% CO ₂ recycle		50% CO ₂ recycle	
	<i>Index value</i>	<i>Index value</i>	<i>Difference, %</i>	<i>Index value</i>	<i>Difference, %</i>
IPCC-Greenhouse effect t CO ₂ (100 years) ^a	8,460	8,045	5	8,253	2
CML-Air acidification ^b t H ⁺	3.0	2.8	5	2.9	3
CML- Depletion of nonrenewable resources ^b	1.7x10 ⁻¹⁵	4.2x10 ⁻¹⁴	-2,354	2.2x10⁻¹⁴	-1,177
CML-Eutrophication t PO ₄	4.9	18.8	-285	11.8	-143

^aIPCC = Intergovernment Panel on Climate Change, United Nations.

^bCML = Centre of Environmental Science, Leiden University, The Netherlands.

The natural resource depletion values are driven to a large degree by how much of a designated natural resource (coal, oil, phosphate, natural gas, uranium, bauxite, iron, etc.) the system consumes. The natural resource depletion values for Scenario 1 are driven by the production of the algae. However, it is not the actual process that is the driver, but rather the upstream emissions from the production of raw materials used in the process (ammonia, super phosphate, potassium sulfate, etc.).

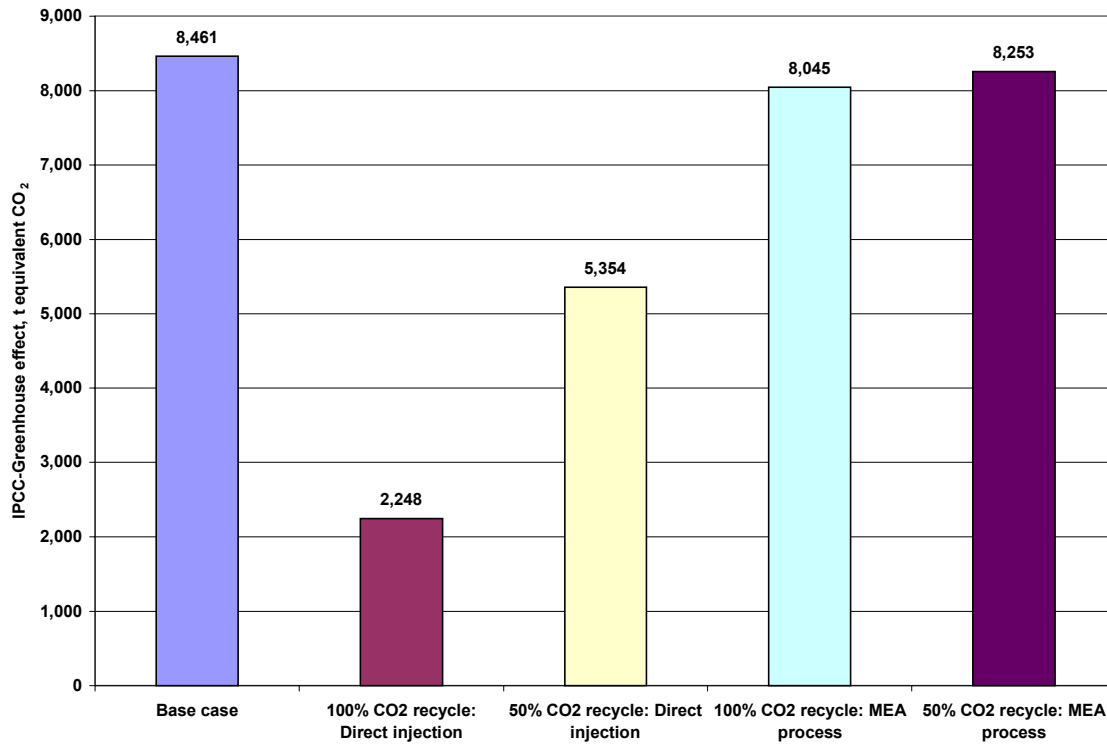


Figure 19. Greenhouse effect for coal firing versus coal/algae cofiring.

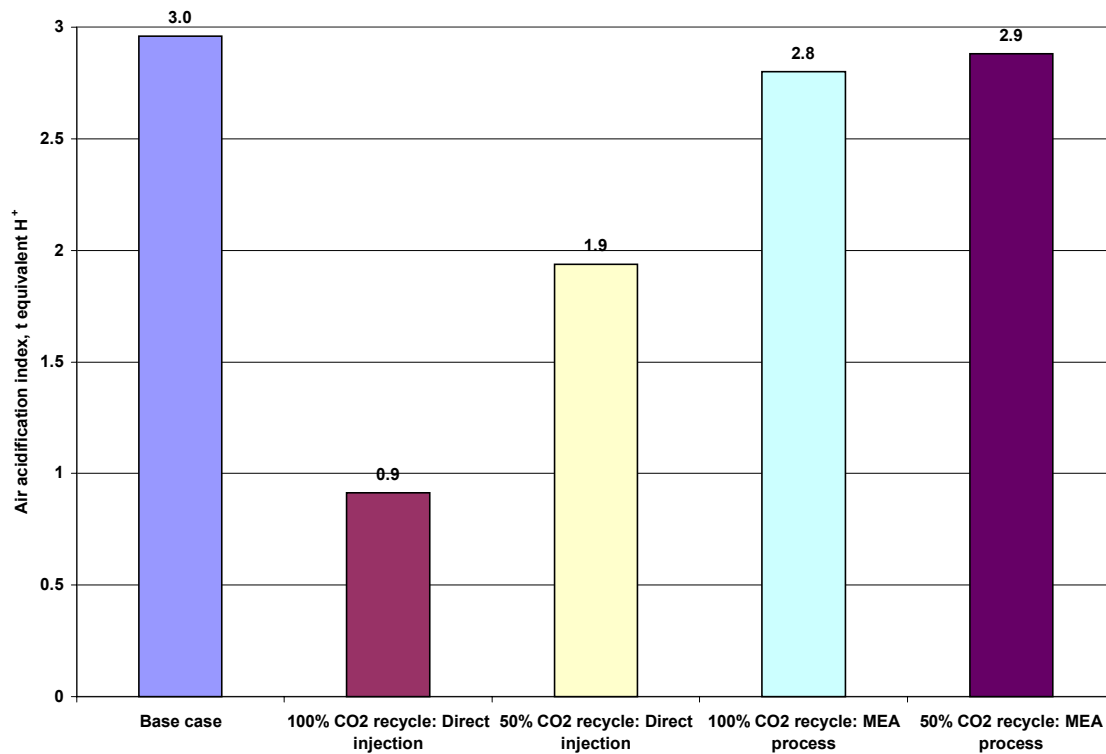


Figure 20. Air acidification potential for coal firing versus coal/algae cofiring.

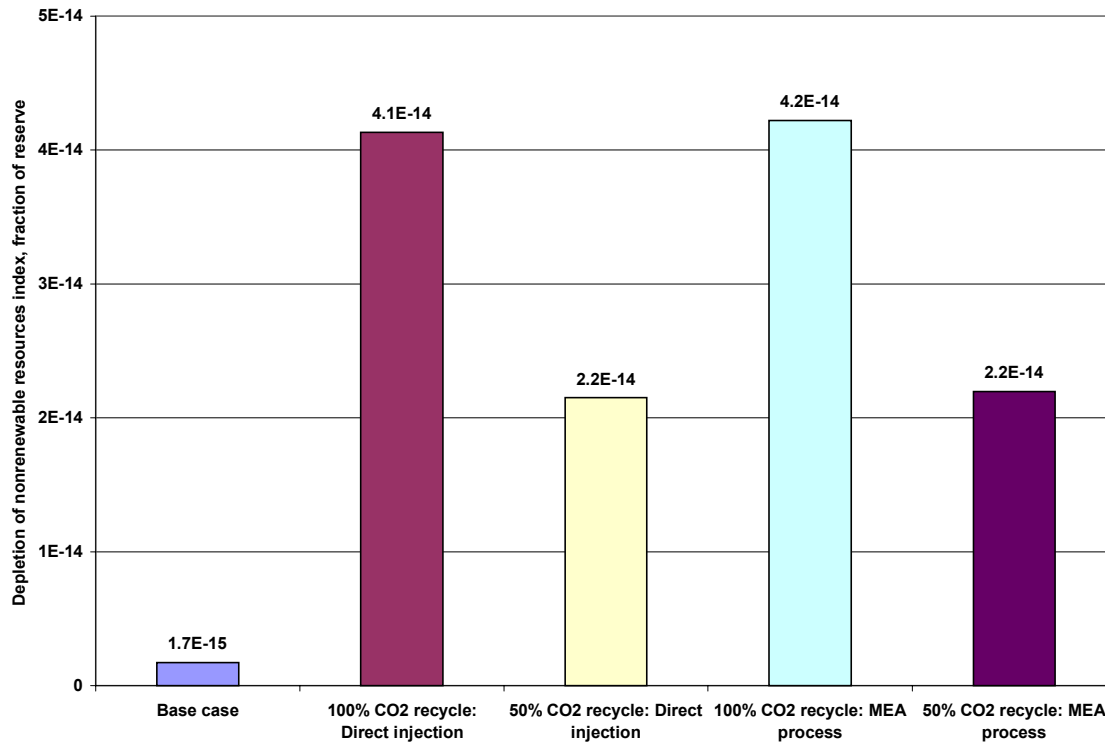


Figure 21. Natural resource depletion potential for coal firing versus coal/algae cofiring.

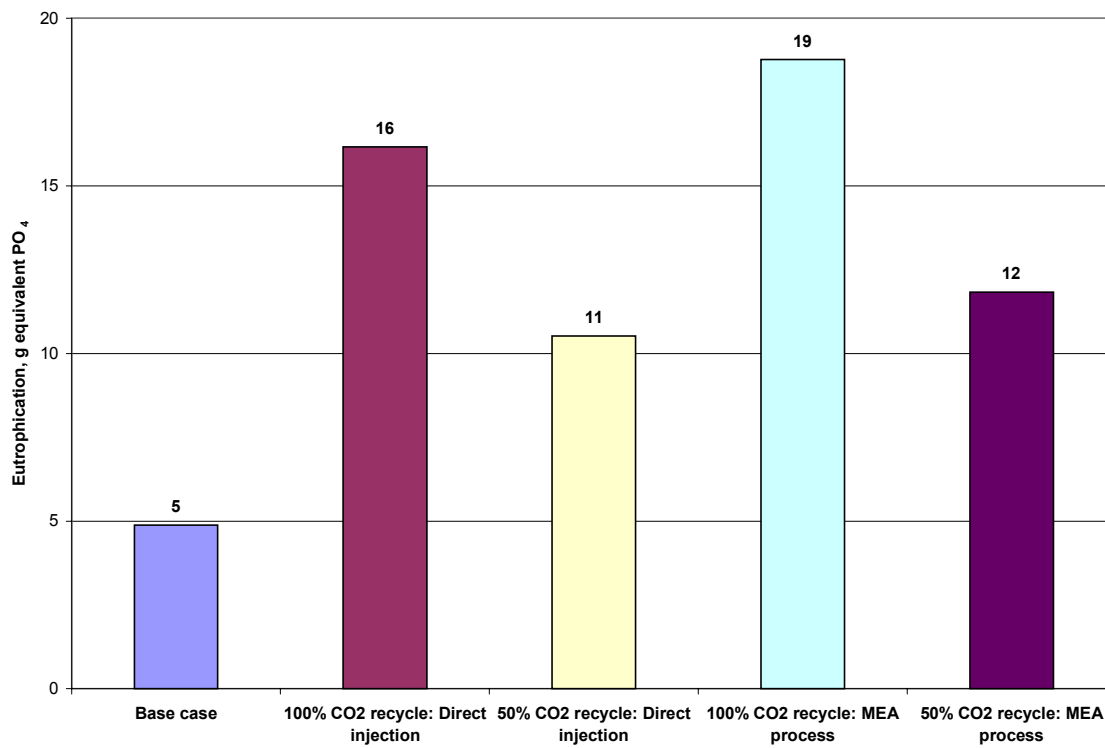


Figure 22. Eutrophication potential for coal firing versus coal/algae cofiring.

For natural resource depletion and eutrophication potential, Scenario 2 is worse than Scenario 1 by similar extents, using either of the production schemes. Natural resource depletion impact is higher because crude oil and natural gas consumption, which lead to enhanced resource depletion, are more pronounced in algae production, and the index depends on consumption *relative* to the reserve. The higher depletion of natural resources results from higher consumption of natural gas and oil for Scenario 2, which have lower reserves than coal. Because coal is being displaced by algae, its positive impact on the index is smaller due to its larger reserves. In other words, if a natural gas fired plant were considered, depletion of natural resources would not be as high for Scenario 2. Also, because consumption is divided by a very large number representing the reserve, the higher coal consumption for the MEA process is somewhat tempered. Hence, both the processes have similar burdens in relation to the natural resource depletion impact.

The eutrophication potential values are higher because of fertilizer consumption during algae production, which results in higher CODs and phosphates. Fertilizer is consumed only during algae production. Hence, both the processes have similar burdens pertaining to the eutrophication index.

8 CONCLUSION

The LCA performed in this study demonstrates that there are potentially significant benefits to recycling CO₂ toward microalgae production. Overall the results show that there are significant differences between Scenarios 1 and 2 (CO₂ conversion to algae and cofiring, and coal firing, respectively); the magnitude of these differences varies with the type algae production process.

Based on the LCA results, lower net values for the algae cofiring scenario were observed for the following using the direct injection process (in which the flue gas is directly transported to the algae ponds):

- SO_x and NO_x
- Particulates
- CO₂ and methane
- Fossil energy consumption

Carbon monoxide and hydrocarbons (except methane) emissions were statistically unchanged, i.e., their variation fell within the accuracy of the study. However, the algae cofiring scenario also suffers from higher water-borne emissions as indicated by the COD values.

The four impact assessment categories evaluated—greenhouse potential, depletion of natural resources, air acidification potential, and eutrophication potential—showed mixed results. The lower carbon dioxide and methane emissions, which—although not regulated or mandated by state or national laws—are also desirable attributes as they lead to lower greenhouse potential for the coal/algae cofiring scenario. Lower values for the algae cofiring scenario, when compared to the coal-firing scenario, were also observed for the impact assessment category of air acidification potential. However, impact assessment for depletion of natural resources showed much higher values. The higher depletion of natural resources results from higher consumption of natural gas and oil for Scenario 2, which have lower reserves than coal. As coal is being

displaced by algae, its positive impact is smaller due to its larger reserves. This means that when comparing to a natural gas fired plant, the relative depletion of natural resources would not be as severe for Scenario 2. The eutrophication potential values are higher because of fertilizer consumption during algae production.

The algae cofiring scenario demonstrates lower GHG (a global unregulated environmental criterion) and air pollutant burdens (local regulated environmental criteria). However, these benefits have to be balanced with higher natural gas and oil use along with a higher eutrophication potential. This LCA affords us an overall picture of impacts across different environmental boundaries. Hence, it can be of help to companies like Rio Tinto Energy Group (a mining/energy company in Australia) and Arizona Public Service that are considering microalgae production as an avenue for GHG mitigation, in their decision-making process.

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APPENDIX A: SOLAR DRYING

A background on solar drying in general and a few specific applications are discussed here.

Crop Drying

In contrast to water heating and the generation of electricity, crop drying utilizes the sun's energy directly. In the tropics, many crops such as cocoa and coffee beans have for decades been dried on racks placed in the sun. Because solar energy is available everywhere, it can be collected and used at the points of greatest need and/or convenience (Brace Research Institute 1975). For crop drying applications, there appears to be little economy of scale in the collection and use of solar energy (Foster et al. 1980). This is beneficial for smaller farms and operations.

Solar energy is an excellent alternative source of supplemental heat for low-temperature grain drying systems. Because these systems require only a few degrees additional temperature rise (5-10°F), they are well adapted to the moderate heat increases that solar energy can economically generate. The fact that solar energy collection is intermittent (i.e., available only when the sun shines) poses less of a problem in drying grain than in comfort heating of a livestock shelter or a home. Solar energy is collected during daylight hours only, which means a variation in drying potential between day and night. But, because low-temperature drying takes several days, the grain can tolerate the varying levels of heat input. "Excess energy" is stored in the form of over-dried grain, which at night will absorb excess moisture from high-humidity air, so that drying can proceed. In effect, the batch of grain being dried provides its own solar heat storage.

Solar Dryers

Most of the information in this section is from the Working Group on Development Techniques (WOT) of the University of Twente, The Netherlands (WOT 1990).

In solar conventional drying, the crop is warmed by the heat from the fire stove, and the air around the heat source is heated up. Under these conditions, the air can take up a great deal of moisture and, by rising, is continually replaced. As the crop, including the air between the plant fibers, is warmed up, the water it contains quickly evaporates. The air within and surrounding the crop is saturated with water vapor. However, the air moving alongside is warm and unsaturated and can take up this moisture and transport it away. A small fan will improve process efficiency, but it is not strictly necessary.

When the air in the room has taken up a certain amount moisture from the crop, the windows mist up (though this will depend on the outside temperature); the air against the cold windows has been cooled to below the dew point. Via this mechanism, water in the crop is transferred to the window panes, where it can be wiped off, or allowed to fall into a gutter, which leads outside the room. If the heat source is replaced by the sun, a solar drier has effectively been described. The cold window, which works as a condenser, is sometimes encountered in indirect drying, where the warming of the air and the drying of the crop are separated, as may happen if the product has been stacked too high or too closely.

Flat-Plate Collector with Cover

The principle underlying the solar collector is that “visible light” falling onto a dark object is converted into tangible heat. The color of the object does not need to be black; instead the absorptive qualities of the material determine the effect. A painted plate can be warmed, but so can a suitable fibrous material such as charred rice chaff.

The cover is of secondary importance, but still has a decisive influence on the total working efficiency; it prevents the heat generated from escaping and also limits the heat loss through re-radiation. Moreover, it allows a controlled air stream to move over the heated objects, which would not otherwise be possible.

To exploit the energy in the heated objects or surface, a medium (water, air) is directed alongside the object. This takes up the heat and transfers it to the desired destination. When air is used, it can pass under the collector, above it, or through canals embedded within it. It can be a “forced” or a “natural” current. The various possibilities are examined below.

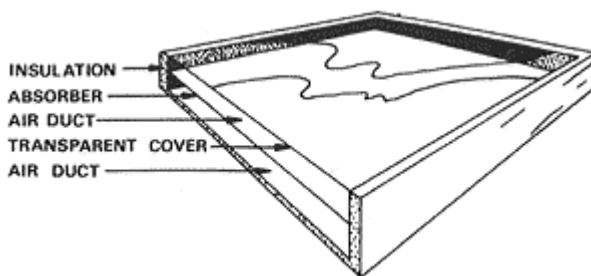


Figure A-1. Simple solar dryer.

Design Elements

Every solar dryer is constructed using the same basic units (Figure A-1), namely:

- ◆ A transparent cover, which admits sunlight and limits heat loss (glass or plastic).
- ◆ A dark absorbent surface, which takes up sunlight, converts it to heat, and transfers this heat to the air within or to the product that needs drying.
- ◆ An insulating layer underneath.
- ◆ An air intake and an outlet, by which means the damper air can be replaced with fresh drier air.

These four elements can be modified if necessary, and/or other elements such as a fan or a chimney may be added.

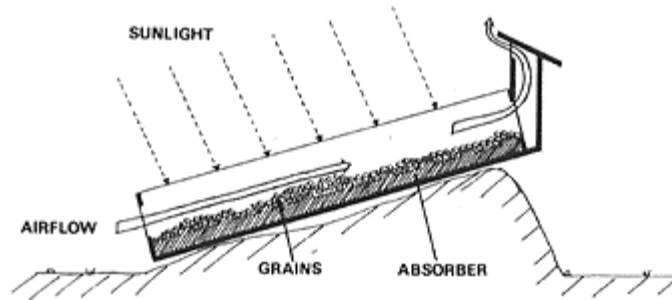


Figure A-2. Solar dryer directly employed.

Direct and Indirect Solar Dryers

Solar dryers can be divided into two categories:

1. Dryers in which the sunlight is directly employed; heat absorption here primarily by the product itself (Figure A-2).
 - ♦ Traditional drying racks in the open air.
 - ♦ Covered racks (protecting against dust and insects).
 - ♦ Drying boxes provided with insulation and absorptive material.
2. Dryers in which the sunlight is employed indirectly (Figure A-3, Figure A-4).

In this method, the drying air is warmed in a space other than that where the product is stacked. The products, then, are not exposed to direct sunlight. Various designs are possible, and these can be further improved by adding powered fans in order to optimize air circulation.

Solar Energy Storage

Excess heat generated during the hottest hours of the day can be stored by passing the air through, for example, a container packed with rocks. This only works in forced circulation systems, as the rocks cause considerable pressure loss in the airflow. Storing solar heat in this way allows the excess heat generated by oversized collectors to be used again during the night for more drying.

Such an installation makes it possible to control the air temperature in the drying room, and thus to ensure that the different drying stages work well (for example, for sowing-seeds). In the first drying stage higher temperatures are allowable because of the considerable free water still present in the product.

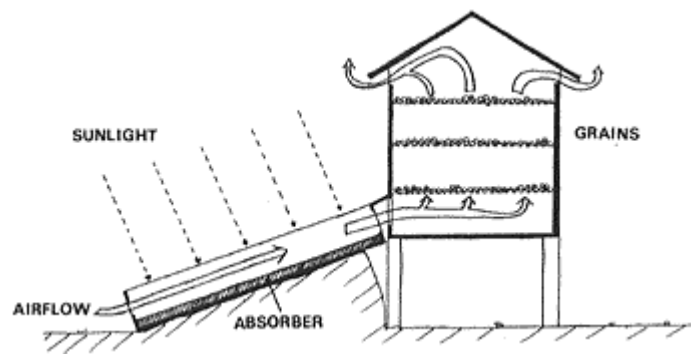


Figure A-3. Solar dryer indirectly employed.

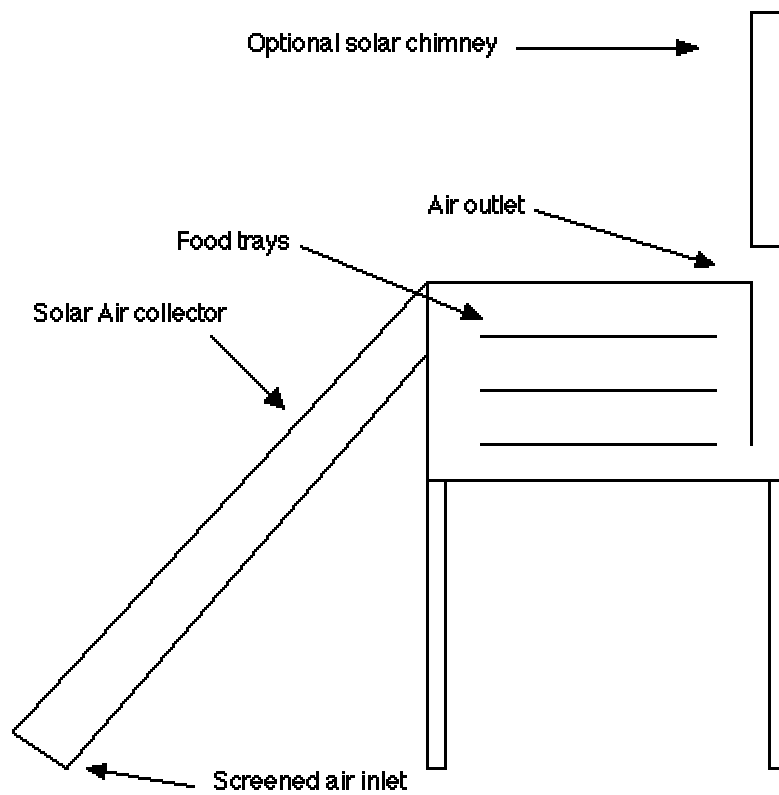


Figure A-4. Schematic of an indirect solar dryer system.

Solar Kiln

Solar drying is also used for drying timber, e.g., using a solar kiln. In a solar kiln, incoming light is changed to longer wavelengths (infrared) by the contents of the “hothouse.” The longer wavelengths cannot exit the hothouse easily due to insulation and non-emitting plastic film and consequently heat the confines. By utilizing this principle, energy savings are realized in solar kilns as compared to conventional kilns at most sites. For example, when drying hardwoods in summer no auxiliary heat is required for most kiln sizes. The control of humidity allows the drying of green and wet timber at required rates.

The estimated operating costs given below are based on costs incurred for actual kilns in the field in Gloucester, Australia (Australian Design Hardwoods, 2000). These operating costs are for a 4.8 m³ kiln averaged over a 4.5 month. The charge was 2” hardwood stock of furniture grade.

- ♦ Electricity: AU\$175 per month
- ♦ Gas: AU\$200–600 per month depending on cloud cover and season
- ♦ Loading: 3 h to load the kiln
- ♦ Monitoring: 1 h per week
- ♦ Plastic replacement: AU\$700–\$1,000 after 2-3years

This cost estimate is for the slowest and most gentle drying regime, and hence, represents the upper cost limit. This field experience demonstrates the technical and economic feasibility of the solar kiln.

Application to Algae

Based on the above discussion, it can be fairly concluded that solar drying is technically feasible for algae dewatering. However, actual experimentation and validation of relevant designs will be needed.

APPENDIX B: IMPACT ASSESSMENT

Background

Only recently has the LCA tool actually been concerned with the impacts of a given system on the environment. By definition, the inventory component of an LCA, still the single focus of many LCA studies, is only concerned with the flows generated by the system (either consumed or emitted), and by definition, does not address environmental impacts.

In the most straightforward and transparent approach to LCI interpretation, the LCI results may be used on an *as-is* basis to help identify and prioritize opportunities for pollution prevention or increases in material and energy efficiency for processes within the life cycle. A particular advantage of LCI applied in this way is its comprehensiveness. LCAs help detect the shifting of environmental burdens from one life cycle stage to another (e.g., lower energy consumption during use, achieved at the cost of much higher manufacturing energy consumption), or from one media to another (e.g., lower air emissions at the cost of increased solid waste). The subsequent stage, LCIA, addresses the issue of how to translate the flows previously compiled into environmental impacts. Some issues viewed as crucial for LCIA are:

- The amount of additional exposure data that would be needed to model actual impacts (as in human health risk assessment) is technically incompatible with the nature of LCA (several hundreds or thousands of processes connected together, each one generating dozens or hundreds of emissions) and does not correspond to its objectives. It should be recognized that LCA is one environmental management tool among several, and that LCA cannot replace a specific environmental impact analysis for a specific site (see Figure B-1).
- Since LCIA aims at assessing potential impacts, LCA should not be considered as a predictive tool for assessing the actual impacts associated with a system, but rather as a tool providing comparative results for the functional unit considered. Moreover, the functional unit often has no reference to time or space considerations (which would be needed for predictive models), but is solely related to the function and performance of a system. As the modeling of environmental impacts improves, potential LCIA models should become increasingly precise and integrate crucial notions such as thresholds (current approaches are all based on a “less-is-better” approach). Consequently, inventory data collection requirements could gradually increase with new parameters characterizing emissions’ location, flow rate, key attributes of impacted media, etc.
- Existing approaches that result in a limited number of indices are highly controversial. They have been criticized because they do not separate the objective evaluation stage of the environmental impact on scientific grounds from the subjective “valuation” stage in which these impacts are traded off. Using such approaches is very dangerous from an industrial perspective, due to the following reasons:
 - * It tends to favor short-term arbitrary choices while masking their arbitrary nature behind quantitative approaches, which convey more rigor and objectivity than are truly involved. This is incompatible with industrial long-term investment and product design.
 - * The choices made might hide pollution displacement from one media to another or from one step to another. In numerous cases, results of inventory or impact assessments have

been conclusive enough so that no valuation was actually needed. Moreover, very often, the existence of trade-offs is by itself a crucial piece of information.

- For most impact categories, variability and uncertainties about impact potentials make any single numerical “equivalency factor” immediately contradictable and discreditable. Instead, LCIA methods need to be developed in which process data and results are considered in probabilistic terms. As for inventory results, uncertainties should be propagated and communicated to the decision-making audience.

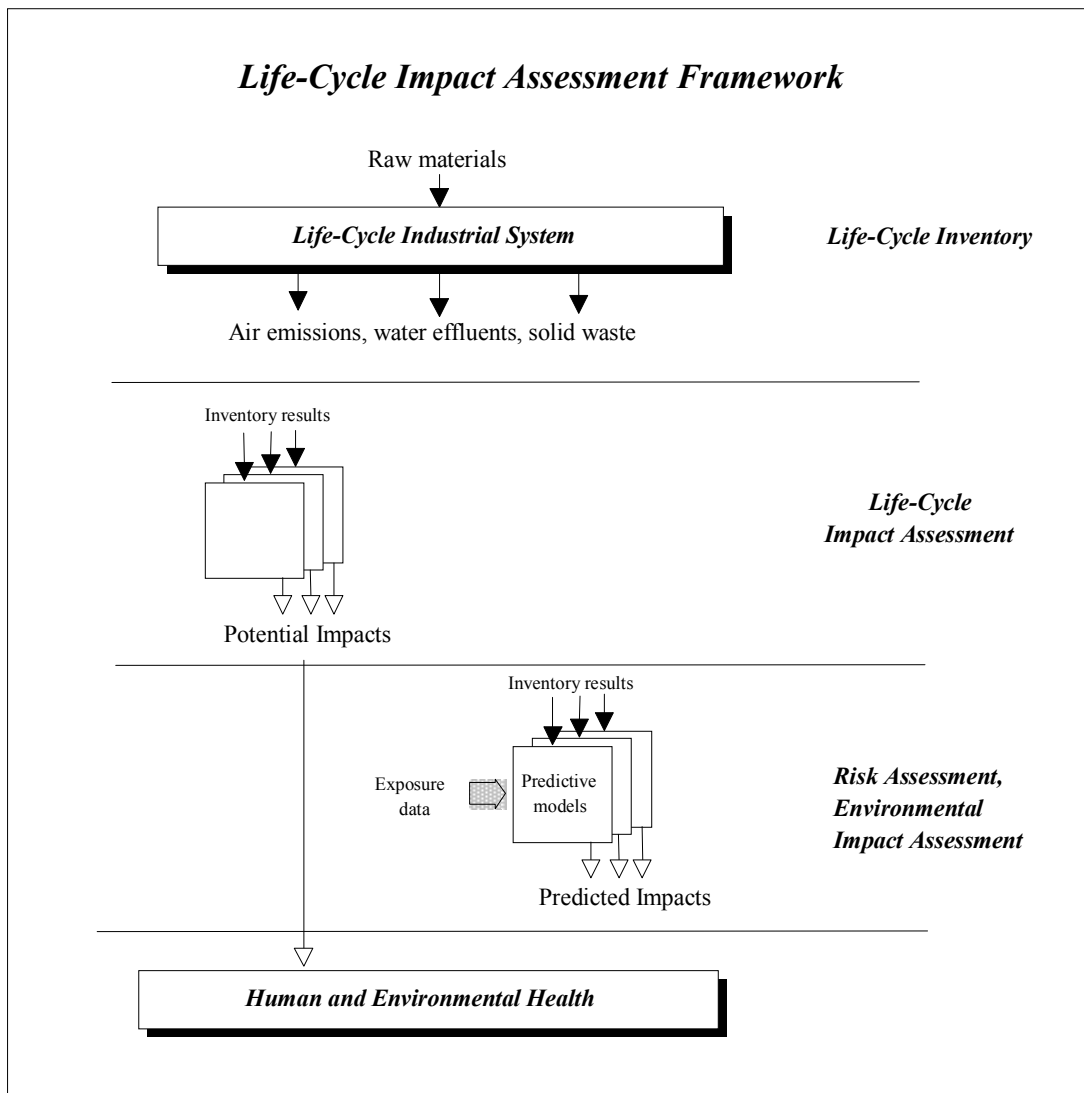


Figure B-1: Life cycle impact assessment framework.

Overview of Life Cycle Impact Assessment Indices

Greenhouse Potential

The Greenhouse potential refers to the ability of some atmospheric gases to retain heat that is radiating from the earth. Models have been developed to quantify the contribution made by emissions of various substances to the greenhouse potential. Generally these models provide an indication of the change in the heat radiation absorption of the atmosphere. Global warming potentials (GWPs) have been calculated to compare the emission of different greenhouse gases (IPCC 1994).

The overall result of emission of these gases on the Greenhouse Potential (E) is calculated as follows:

$$E = \sum GWP_i \times m_i$$

where, for a greenhouse gas i ,

m_i : the mass of the gas released (in kg),

GWP_i : its potential impact on global warming expressed in grams of CO₂ equivalent.

The factors used for calculating the greenhouse potential are listed Table B-1.

Table B-1: Greenhouse gas potential factors

Formula	Substance	GWP
CO ₂	Carbon dioxide	1
CH ₄	Methane	21
N ₂ O	Nitrous oxide	310
CCl ₄	Carbon tetrachloride	1,400
CFCl ₃	CFC 11	4,000

The potential impact on global warming of the gas i can be defined as the ratio between the cumulative radiative force between present and a future time horizon (in this case, 20, 100, and 500 years) as a result of the release of a unit mass of greenhouse gas i now, and an equal emission of the standard gas, carbon dioxide. The calculation of the GWP is based on understanding the fate of the emitted gas and the radiative effect associated with the amount remaining in the atmosphere.

Acidification Potential

Potential acidic deposition (onto soil, vegetation, and water) can be expressed as potential hydrogen ion (H⁺) equivalents. Potentially acidifying emissions of SO₂, NO_x, and NH_x can be aggregated based on their potential to form H⁺. In the calculation of H⁺ equivalents, it is assumed that one mole SO₂ will produce two moles H⁺, that one mole nitrogen oxide compounds (NO_x)

will produce one mole H^+ , and that one mole reduced nitrogen compounds (NH_x) will produce one mole H^+ .

An acidification potential (AP) of a substance is calculated based on the number of H^+ ions that can be produced per mole, given by the stoichiometry of the oxidation reaction (Guinee 1995). However, as emissions are specified in kg rather than in moles, the weight has to be divided by the molecular weight of the substance.

The factors used for calculating the acidification potential are listed in Table B-2.

Table B-2: Acidification potential reactions

Formula	Substance	Reaction	AP
SO ₂	Sulfur dioxide	$SO_2 + H_2O + O_3 \rightarrow 2H^+ + SO_4^{2-} + O_2$	32
NO _x	Nitrogen oxides	$NO_2 + OH^- \rightarrow H^+ + NO_3^-$	46
NH ₃	Ammonia	$NH_3 + 2O_2 \rightarrow H^+ + NO_3^- + H_2O$	17
HCl	Hydrochloric acid	$HCl \rightarrow H^+ + Cl^-$	36.5
HF	Hydrogen fluoride	$HF \rightarrow H^+ + F^-$	20

Eutrophication Potential

Eutrophication is the addition of mineral nutrients to the soil or water, which increases production of cell biomass. In both media, the addition of mineral nutrients (N and P) in large quantities result in generally undesirable shifts in the number of species in ecosystems and a reduction in the ecological diversity. In water, it tends to promote the growth of algae, which eventually die and sink to the deeper layers of the water body. The decomposition of this dead cell biomass requires the consumption of large amounts of oxygen, which can result in the death of other aquatic species, such as fish.

Another form of oxygen deficit may be caused by emissions of organic materials that can bind oxygen. These emissions are generally expressed as the COD or the biochemical oxygen demand (BOD). The oxygen is mainly consumed by the biological degradation of organic content. The eutrophication potential (EP) of a substance is calculated based on its potential cell biomass formation. It is calculated in N equivalents, by considering the average ratio of N and P in cell biomass and the oxygen required for the breakdown of this cell biomass. The ratios for N, P, and O₂ are 7, 1, and 142, respectively.

EPs are developed by analogy with the GWP. Therefore, phosphate ions have been chosen as the reference substance. A single index is produced for the eutrophication:

$$EP = \sum EP_i \times m_i$$

where m_i is the weight (in kg) of the substance released. The calculated quantity indicates the quantity of a PO_4 emission with the same potential eutrophication effect.

The factors used for calculating the eutrophication potential are listed in Table B-3 (CML 1992).

Table B-3: Eutrophication potential factors

Formula	Substance	EP
PO_4	Phosphates	1
P	Phosphorous	3.06
N	Nitrogen	0.42
NO_x	Nitrogen Oxides	0.2
NH_3	Ammonia	0.42
COD	Chemical Oxygen	0.022

Natural Resources Depletion Index

Resource Depletion as an Environmental Issue

Resource depletion can be defined as the decreasing availability of natural resources. The resources considered in this impact are fossil and mineral resources, excluding biotic resources and associated impacts such as species extinction and loss of biodiversity. It is important to recognize that what is addressed in this index is the fact that some resources are depleted, not the fact that their extraction from the environment will generate impacts (e.g., methane emissions from coal mining).

Corresponding Inventory Flows

The assessment of natural resources depletion can only be applied to a subset of the LCI flows called elementary flows, i.e., flows that are directly taken from the environment. A coal consumption of 1 kg at the power plant gate does not correspond to an elementary flow. Rather, it corresponds to a consumption of approximately 1.03 kg of coal in the ground, due to the losses in mining, processing, and transportation.

Availability Defined

The notion of availability can be further defined. Natural resource depletion does not take into account the availability within the economy, but rather the availability within the “natural” environment. Excluded from this impact are “economic stocks” such as aluminum from aluminum cans or steel from used car bodies. Therefore, the availability is not measured within the whole economy, but only at the economy/environment “boundary.” Furthermore, the availability is concerned with the availability within the primary extraction medium (e.g., iron ore available from the earth’s crust) and not within the entire geosphere (which would include iron available in water bodies, atmosphere, plants, landfills, etc.).

Resource versus Reserve

Once the concept of availability has been defined, the notion of reserve of a resource needs also to be determined. Through the years, geologists, mining engineers, and others operating in the

mineral field have used various terms to describe and classify mineral resources. Known resources can be classified from two standpoints: 1) purely geologic or physical/chemical characteristics—such as grade, tonnage, thickness, and depth—of the material in place, and 2) profitability analyses based on costs of extracting and marketing the material in a given economy at a given time. The former constitutes important objective scientific information of the resource and a relatively unchanging foundation upon which the latter economic delineation can be based.

For mineral resources, the reserve chosen for this index is the reserve base as defined by the U.S. Bureau of Mines (USDOJ 1994): reserve base is “part of an identified⁴ reserve that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality thickness, and depth. The reserve base encompasses those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. It includes those resources that are currently economic (reserve), marginally economic (marginal reserves) and currently sub-economic.” By including economic and sub-economic considerations, the reserve base falls between the two extremes of economic reserve and ultimate reserve/resource base.

For fossil fuels (including uranium), the reserve chosen is based on information supplied by the World Energy Council (WEC). In order to be consistent with the reserve base used by the U.S. Bureau of Mines, the reserve chosen for fossil fuels has been defined as the addition of the WEC’s “proved amount in place” (tonnage in place that has been both carefully measured and has also been assessed as exploitable under present and expected local economic conditions with existing available technology) and “estimated additional reserves recoverable” (quantity of the estimated additional amount in place that might become recoverable within foreseeable economic and technological limits).

It should be noted that what matters most in this impact assessment index is the availability of a relative scale allowing comparisons between resources rather than an estimation of the exact size of what is considered available for use. This is linked to the fact that impact assessment as performed within an LCA is of a comparative rather than predictive nature. It aims at assessing the relative potential impacts of different alternatives (i.e., natural resource depletion index of option A versus option B) rather than assessing the actual impacts of a system onto the environment (as it would be done in traditional risk assessment).

Index Definition

Once the type of reserve is identified, an index can be defined that will relate an inventory flow with the depletion of that resource. The proposed depletion index uses equivalency factors, i.e., each natural resource consumption recorded in the inventory is multiplied by the resource’s weighting factor (or equivalency factor). As described in equation (1) below, the total depletion index is then compiled by adding the previous intermediate results for all inventory flows considered.

⁴ As opposed to identified resources are undiscovered resources, the existence of which is only postulated.

Several methods can be used to produce the equivalency factors. In the first method described in equation (2), the inverse of reserve (in kg) is used as a weighting factor. Such an index addresses the relative contribution of the LCA system to the depletion of the reserves (the larger the relative contribution, the bigger the index) as well as the size of the reserve (the larger the reserve, the smaller the index). However, it does not address the following problem: how long a given resource will continue to be available (the fact that the reserve is rapidly or slowly being depleted, which is directly related to the notion of sustainability, is not accounted for in this index).

In the second method, described in equation (3), the inverse of remaining years of use is used as a weighting factor. The number of remaining years of use is defined as the reserves divided by the total world-wide production (i.e., extraction). It represents the number of years for which current reserves will suffice at the current production (extraction) level. This index, however, does not correctly account for the size of the reserve: two resources with the same number of years will have the same indices irrespective of whether there are 1 kg or 1 million t reserves.

In the third method described in equation (4) and retained as a basis for the index, the inverse of remaining years of use and the reserve size are used as weighting factors. This index addresses both problems that were raised by the first two methods. It should be noted, however, that choosing higher (e.g., cubic) power for the reserve and production could generate a number of similar indices.⁵ Since there is no rational basis for doing so, the index has been kept as in equation (4). In order to facilitate the readability of the results, all equivalency factors have been multiplied by 10^{15} (as explained previously, the relative contribution of each resource is what matters most).

$$\begin{aligned}
 (1) \quad Depletion &= \sum_{res} \text{equivalency factor}_{res} \times \text{inventory consumption}_{res} \\
 (2) \quad Depletion &= \sum_{res} \frac{1}{\text{reserve}_{res}} \times \text{inventory consumption}_{res} \\
 (3) \quad Depletion &= \sum_{res} \frac{1}{\text{years}_{res}} \times \text{inventory consumption}_{res} = \sum_{res} \frac{\text{production}_{res}}{\text{reserve}_{res}} \times \text{inventory consumption}_{res} \\
 (4) \quad Depletion &= \sum_{res} \frac{1}{\text{reserve}_{res} \times \text{years}_{res}} \times \text{inventory consumption}_{res} = \sum_{res} \frac{\text{production}_{res}}{(\text{reserve}_{res})^2} \times \text{inventory consumption}_{res}
 \end{aligned}$$

⁵ It has been shown that in order to keep the index independent of the resource density, the power of the reserve should be the power of the production plus one, which is the case in equation (4).

APPENDIX C: PROJECT REVIEW

The draft Final Report (which contained the LCA results, as well as the scoping decisions and data summary) was reviewed by the following panel. Their comments were incorporated into the final version.

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